ETH zürich

D MAVT *Chair of Micro- and Nanosystems*

Hallcube - from prototype to product

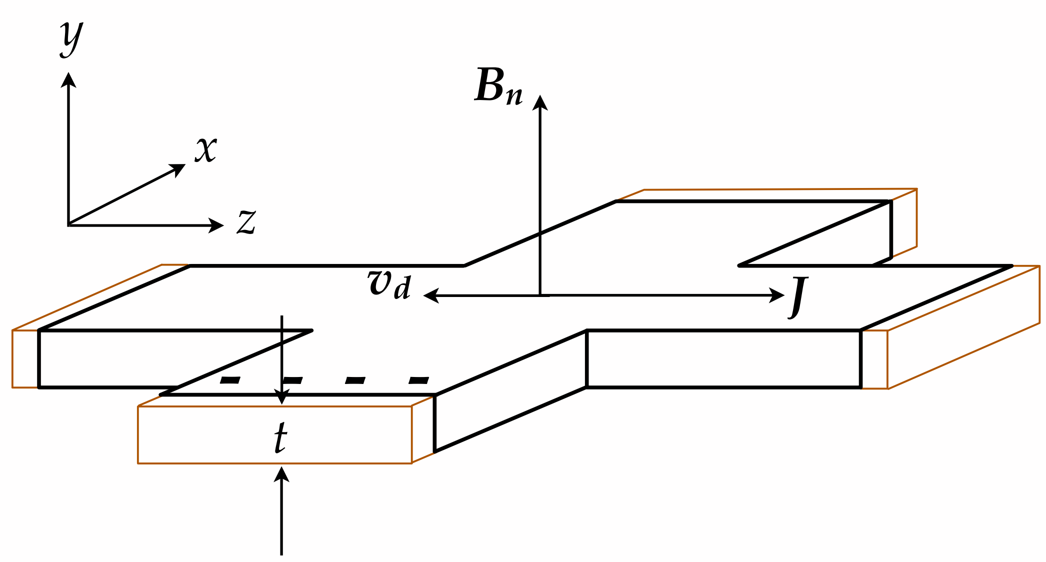
Christina Wouters

IMMW20, Diamond Light Source, 06.06.2017

1D to 3D Hall sensors

- Hall sensor considerations: offset, linearity, sensitivity, temp. coeff., angular alignment, planar Hall effect, induced voltages, noise, magnetoresistance, active area/volume, stability

$$\boxed{V_{out} = V_H + V_{PH} = R_H \frac{I}{t} B_y + R_{PH} \frac{I}{t} B_x B_z = R_H \frac{I}{t} B_n + R_{PH} \frac{I}{2t} B_p^2 \sin 2\theta}$$



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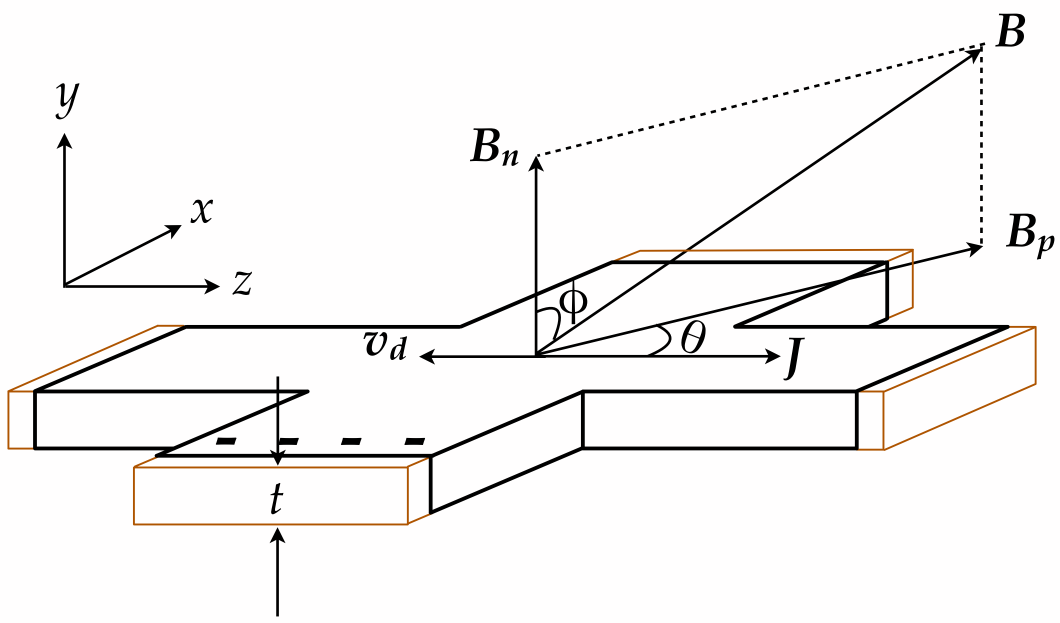

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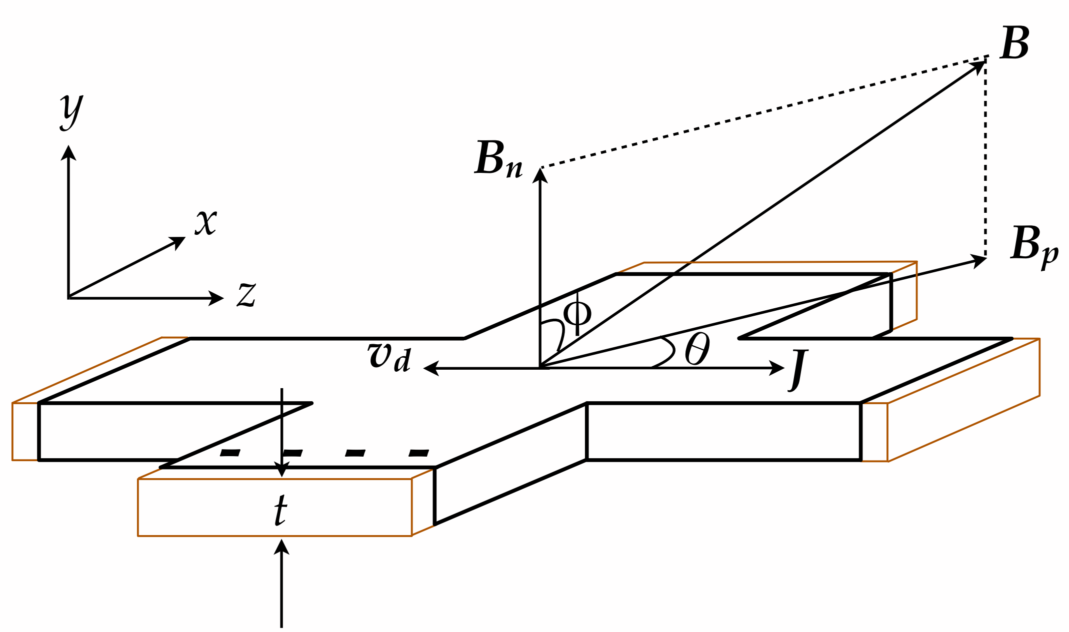

100 ppm accuracy at 1 T (1 Gauss) can be routinely achieved with 1D Hall sensors:

- Precision electronics
- Careful sensor alignment
- Temperature stabilization or control
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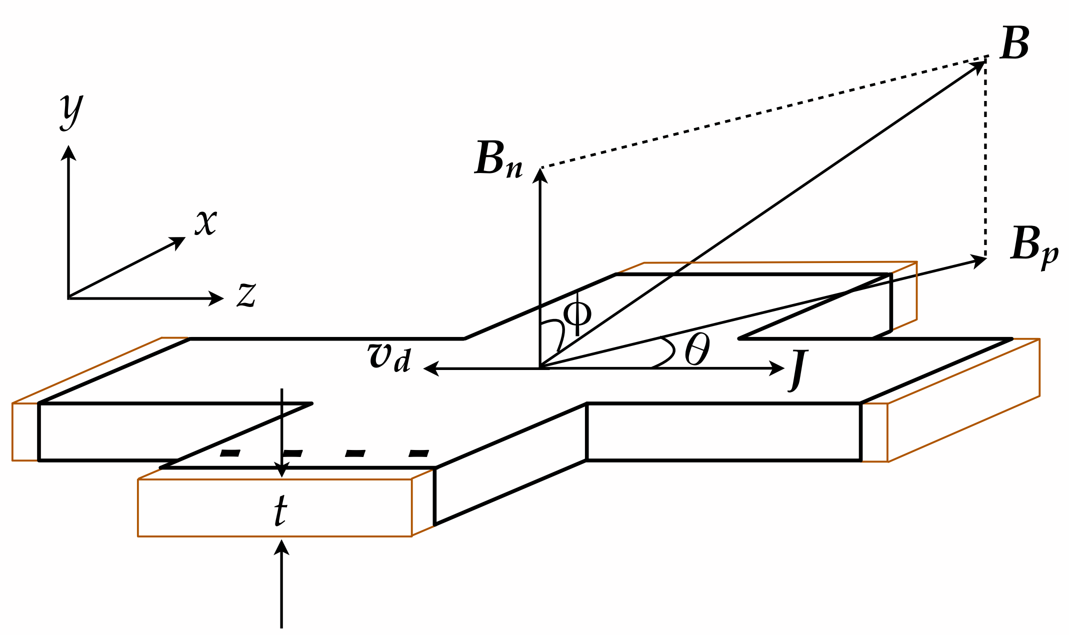

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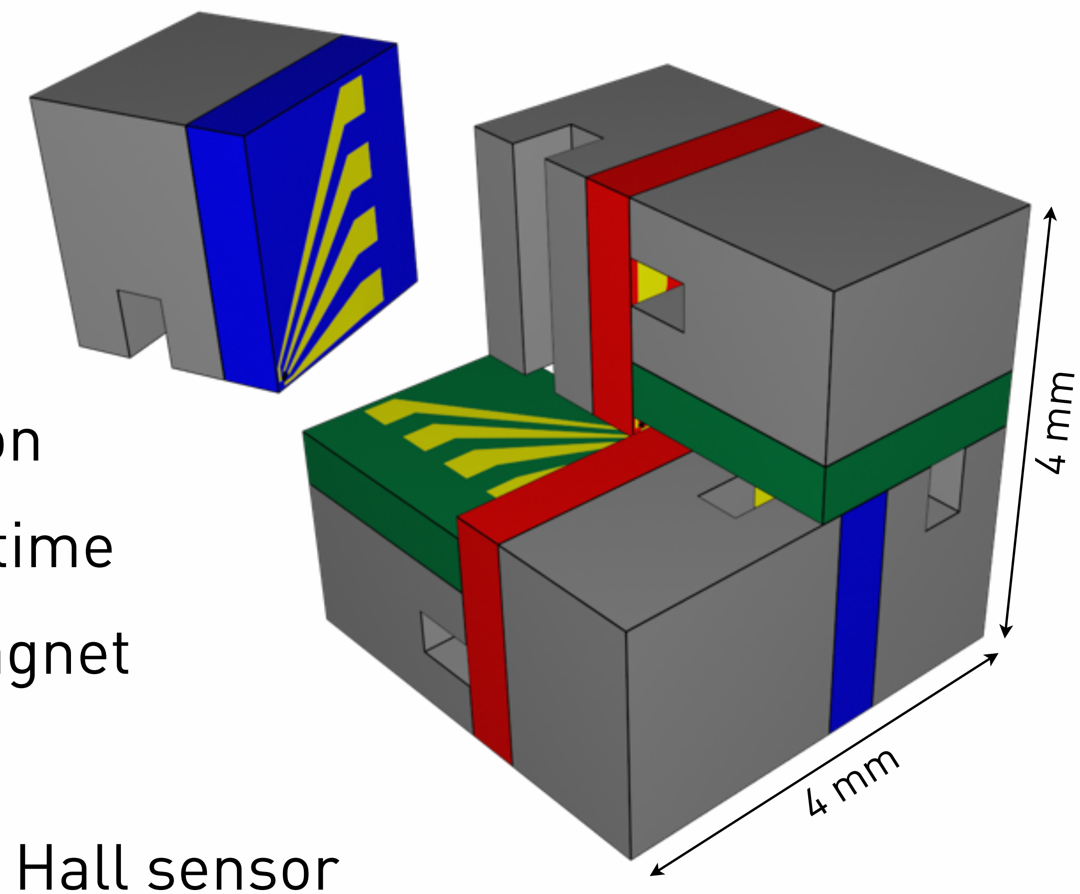
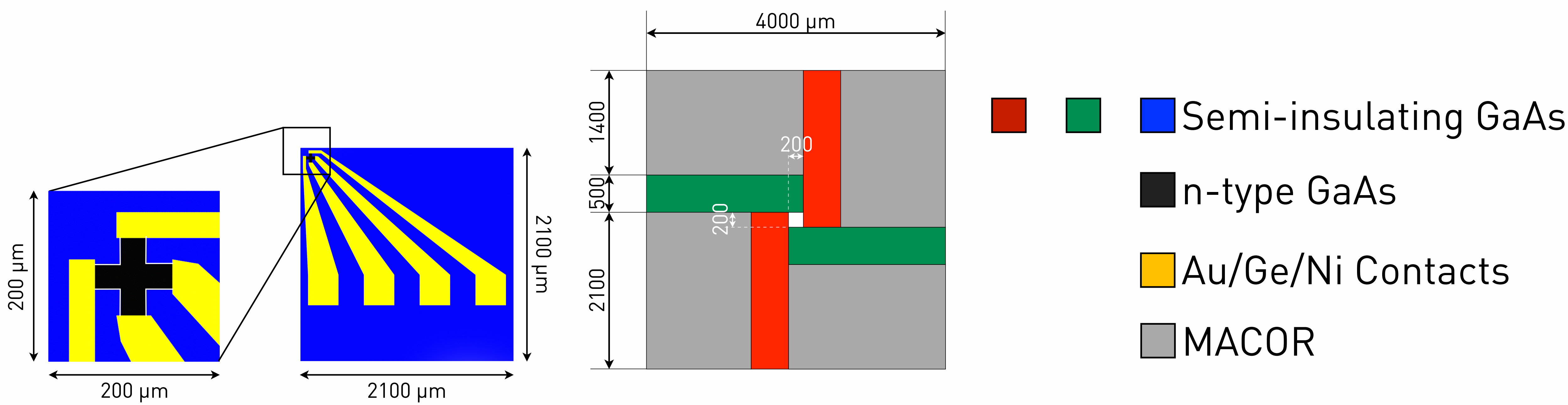
- Exploit the good precision of 1D Hall sensors ("Hall plates") to create from them an equally good **3D Hall sensor**

Hallcube in a nutshell



- Active volume (200 μm)^3
- One sensor pair (red, green, blue) per field direction
  - Measure ***B*** virtually in single point in space and time
  - Cancel out loop-induced voltages (on-the-fly magnet measurement)
  - Cancel out planar Hall voltage (***B***$_p$ in plane to 1D Hall sensor → cross-sensitivity)
- Target accuracy: <100 ppm at the 1 T level for *any* magnetic field direction



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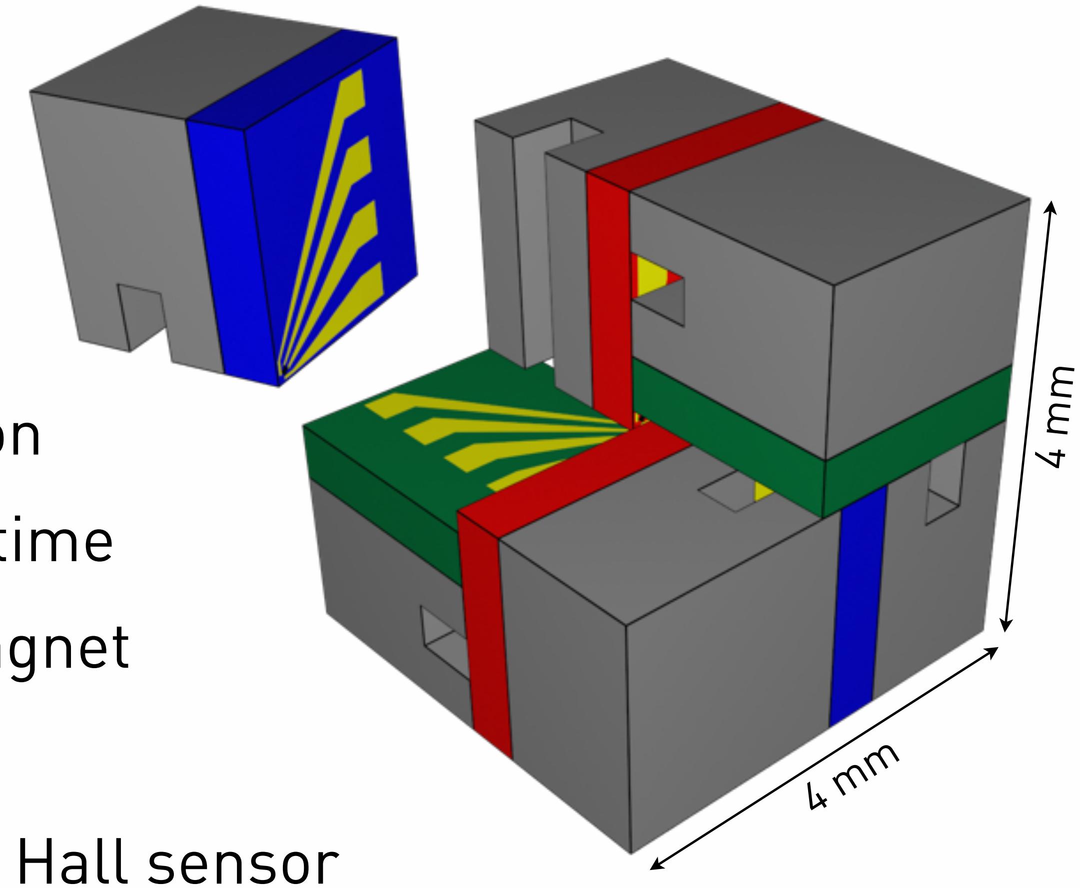

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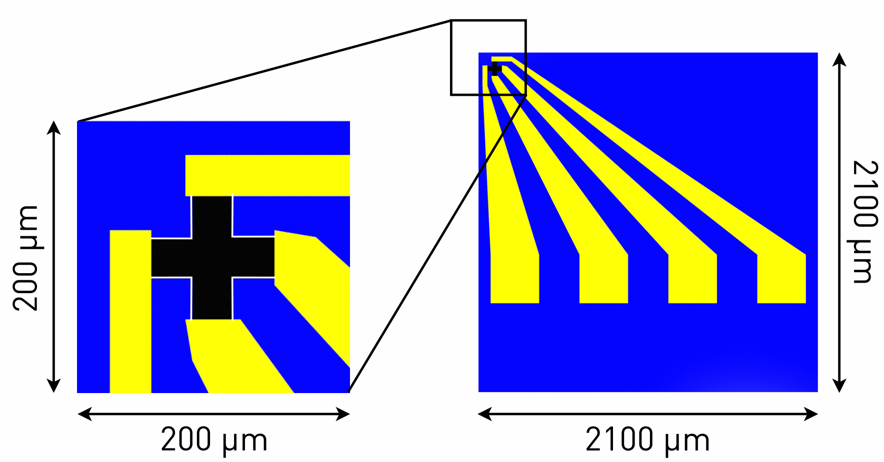

Hall sensor parameters:

- S = ~100 mV/T (I = 1 mA)
- Offset < 10 Gauss
- Non-linearity (0 - 2 T) max 10 Gauss
- Temp. coeff. ~ 200 ppm/°C
- V_{pp} (short term) < 2 μV (or 20 ppm)

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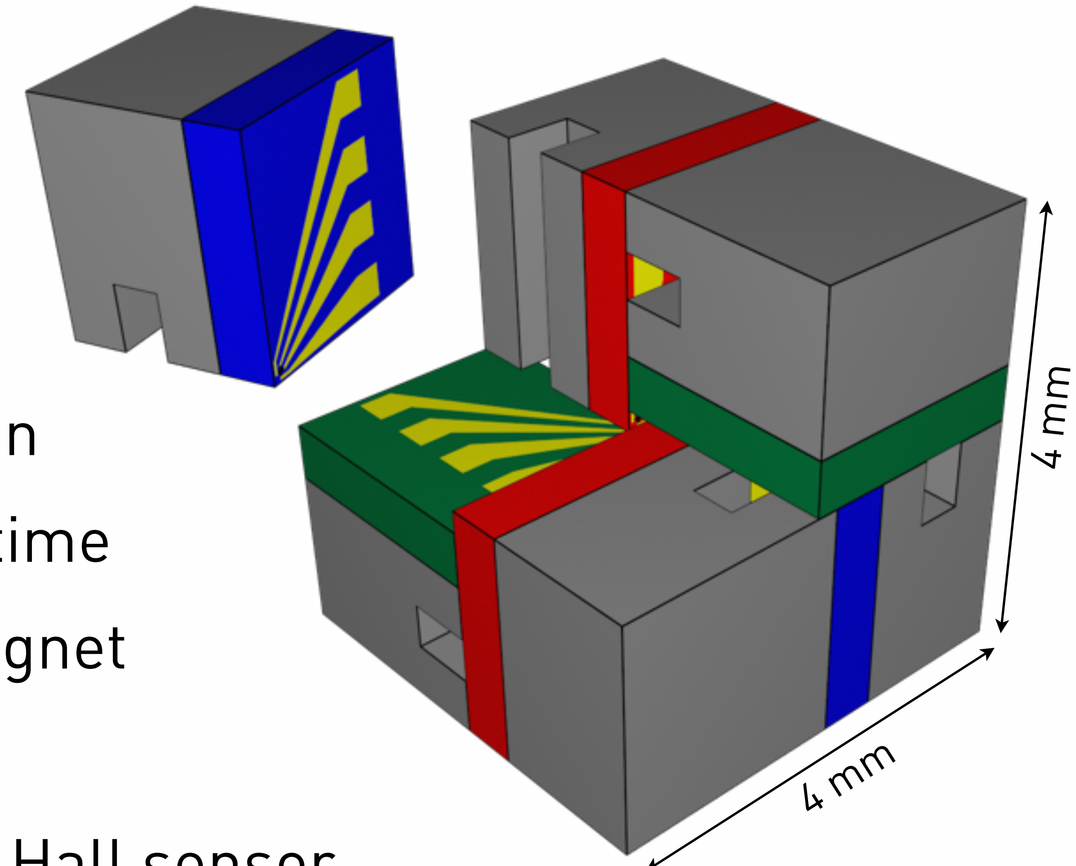

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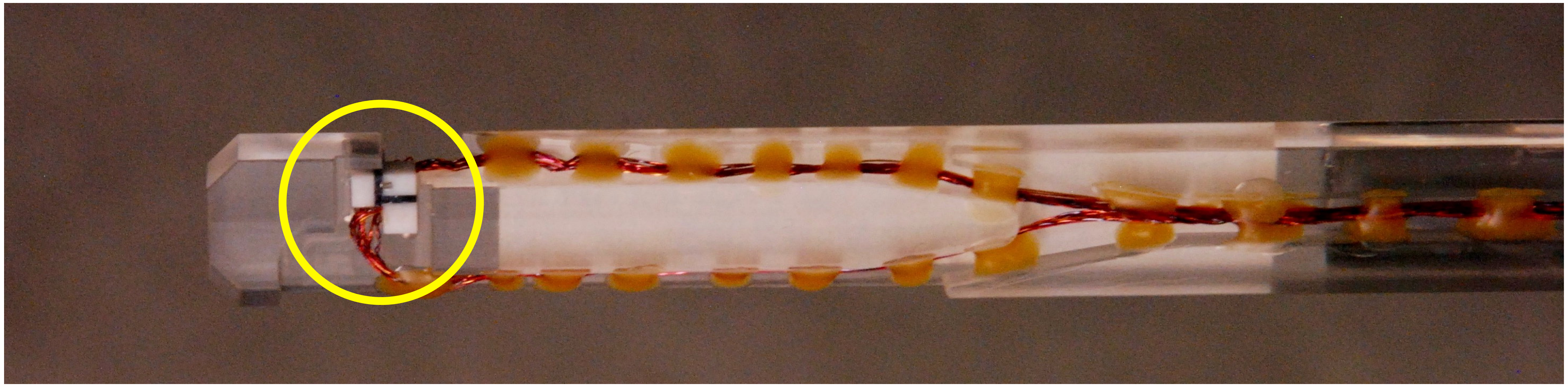

Design implications

- Three sensor pairs, Hall voltages assigned practically to a single point. Interpolation error quadratic field distribution:

  For d = 200 µm and for a tolerable error of <100 ppm: fields $B_x(x)$, $B_y(y)$, $B_z(z)$ up to 10.000 Tm^{-2}

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$$\mathbf{B} \cdot \mathbf{n} = |\mathbf{B_y}| \cos\phi \approx B_y \text{ for small } \phi$$
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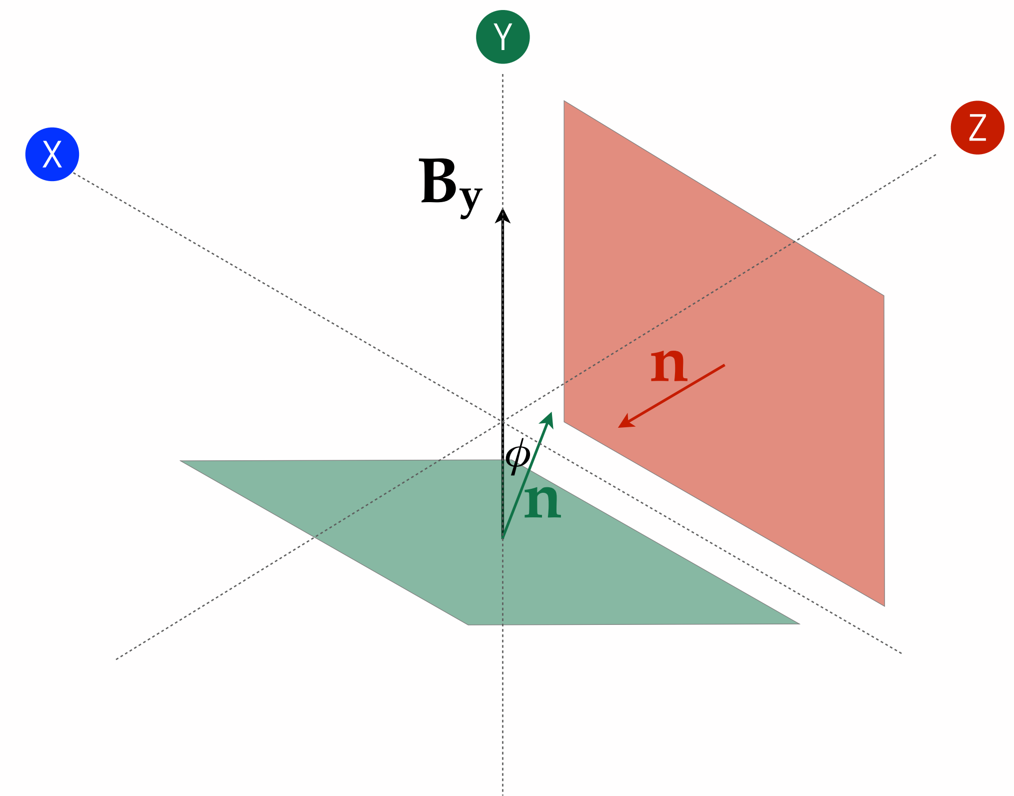

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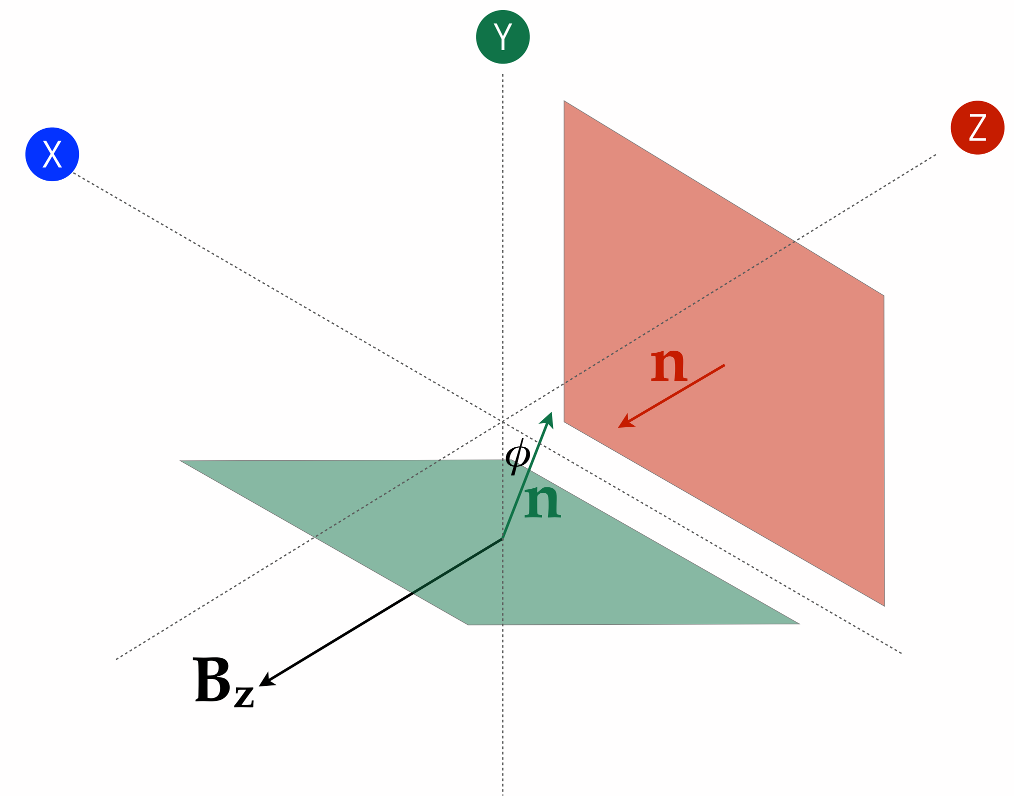

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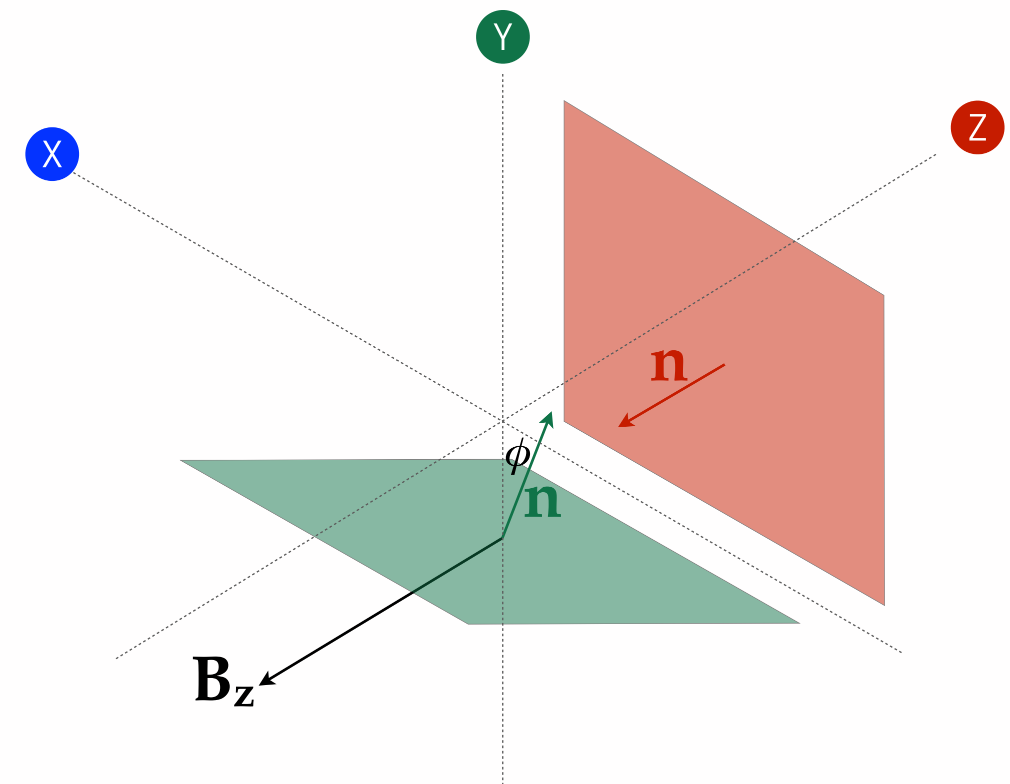
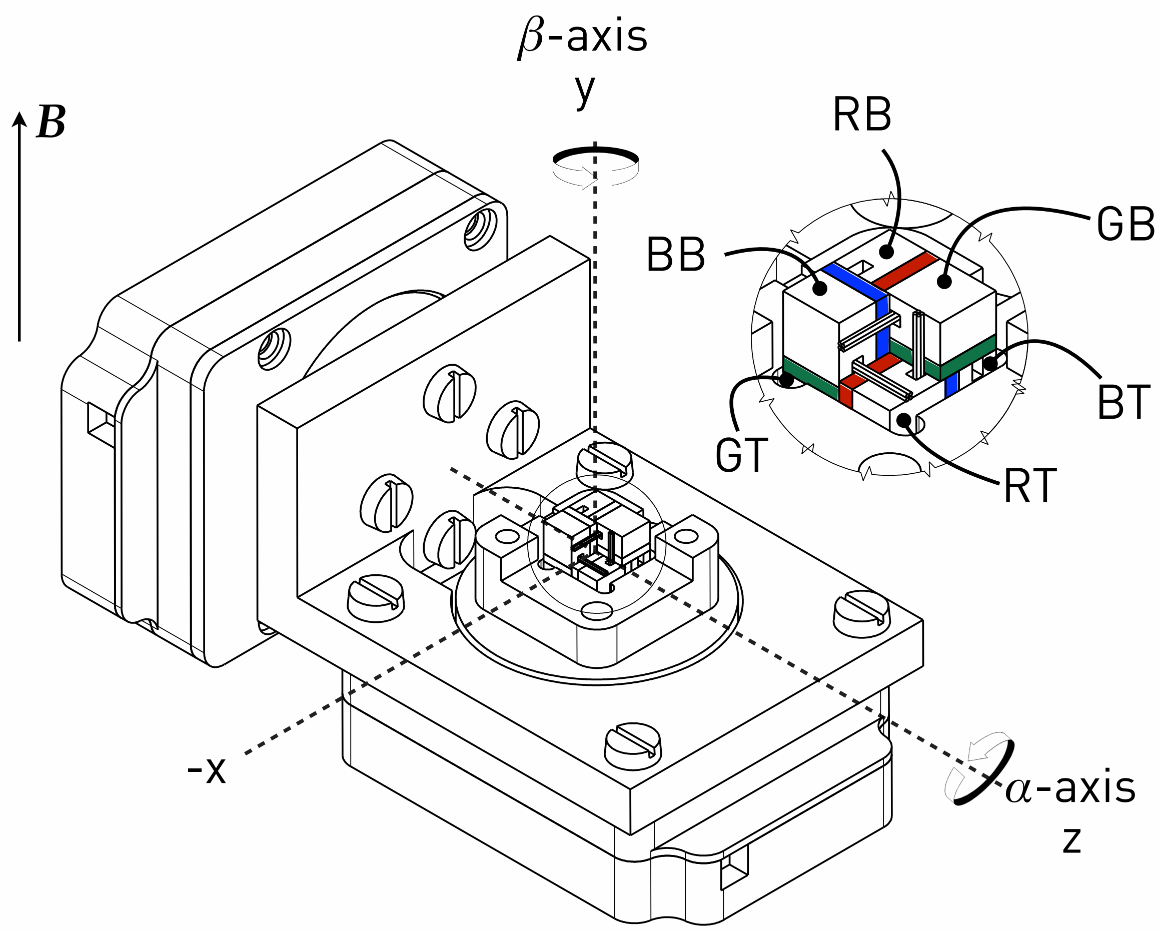


> <100 ppm cross sensitivity → <0.1 mrad or 0.006° orthogonality error

Orthogonality errors



Harmonic Analysis

$B \approx 1$ T

360° rotation around one axis (α or β)

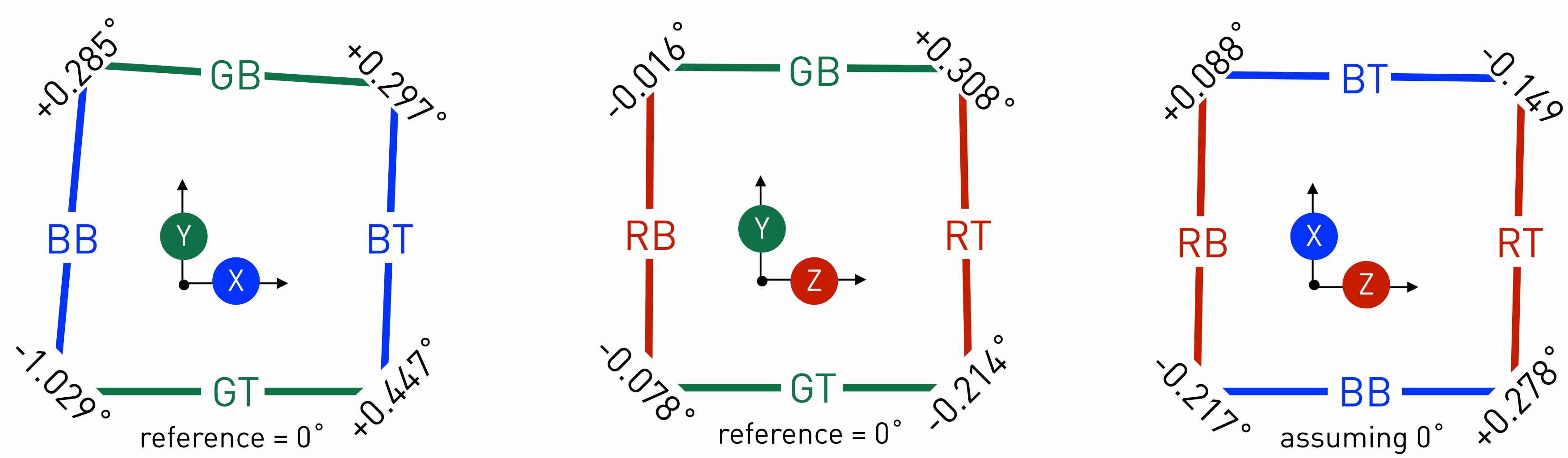
E.g. around α at given β:

$$A_0 + A_1 \cos(1\alpha - p_1) + A_2 \cos(2\alpha - p_2)$$

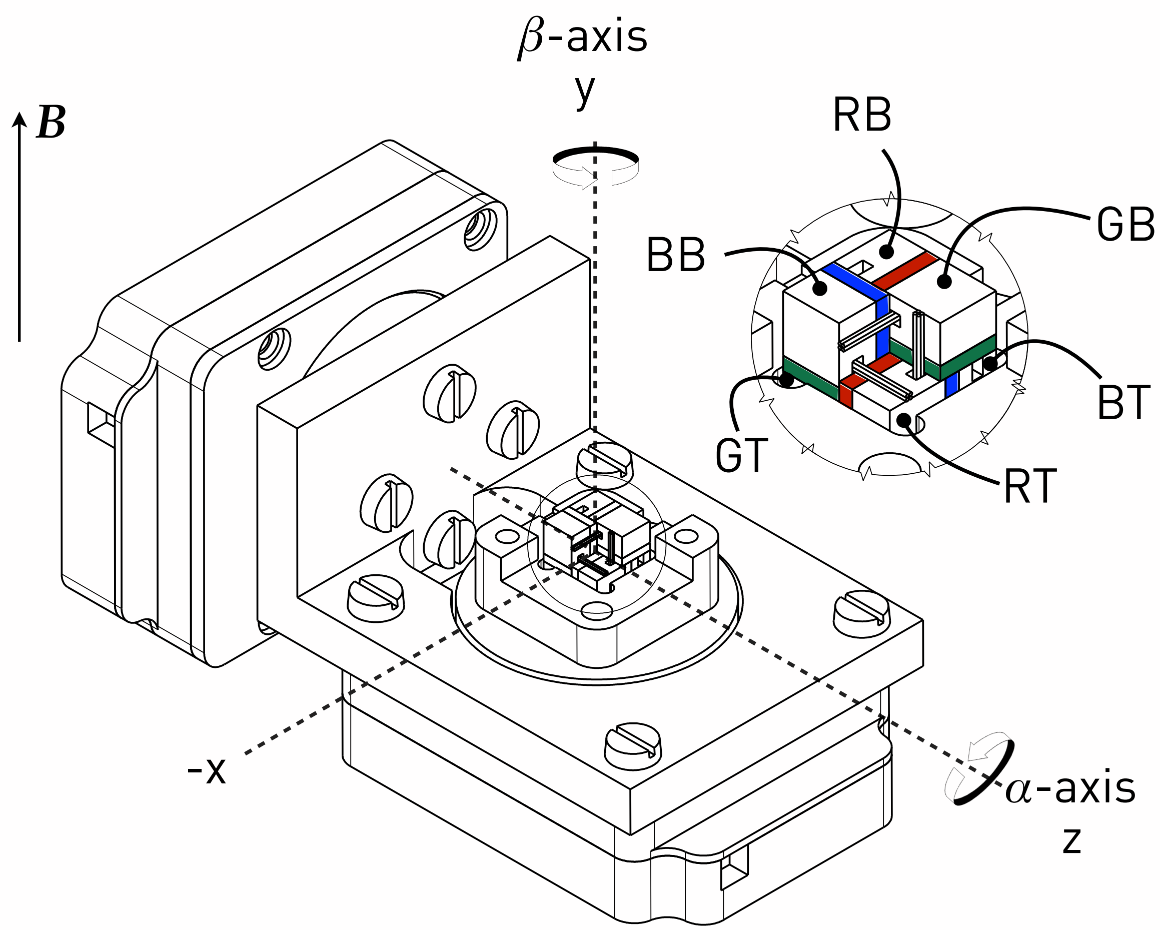
0^{th} harm: offset, $\boldsymbol{B} \cdot \boldsymbol{z} \neq 0$

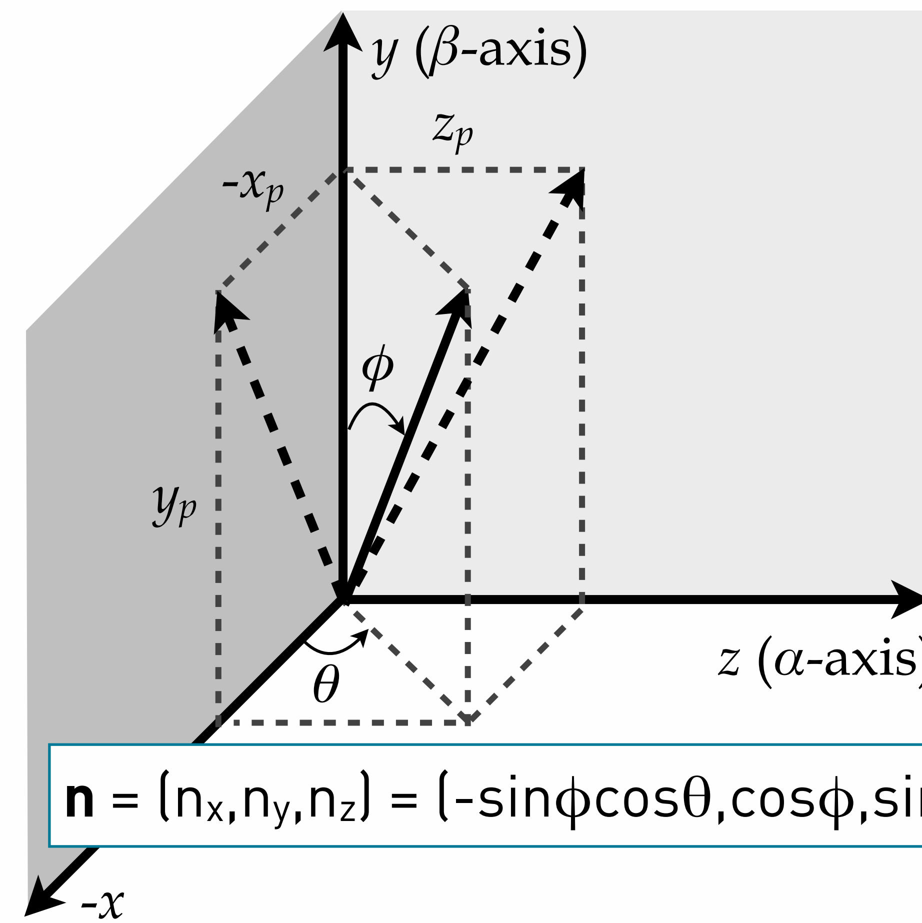
1^{st} harm: Hall effect

2^{nd} harm: planar Hall effect



Field reconstruction





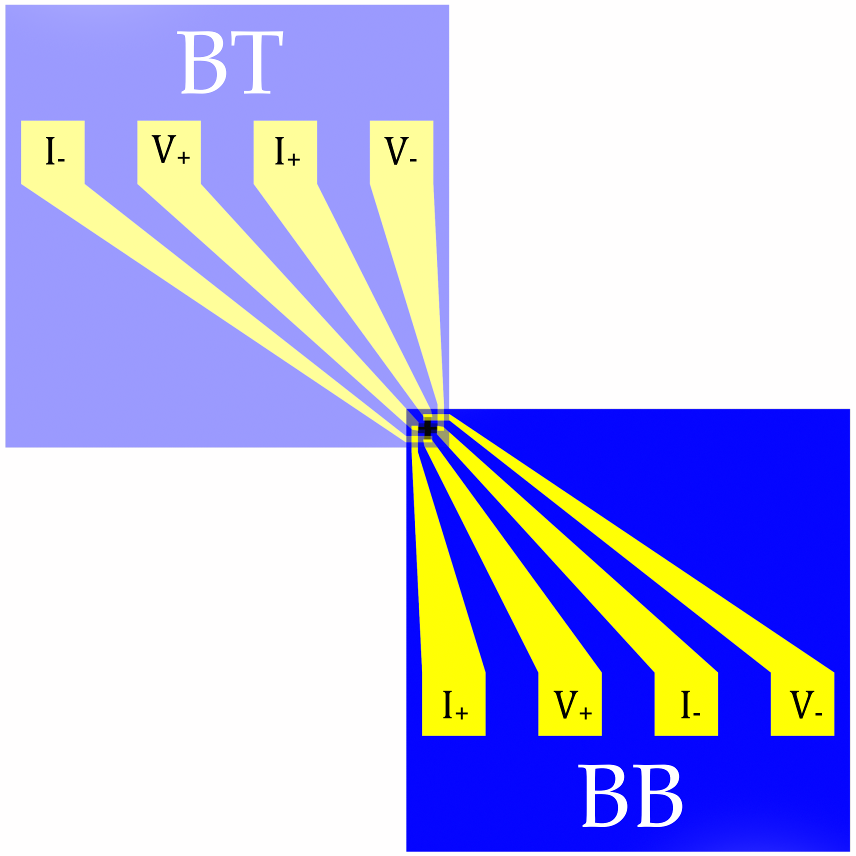
n = $(n_x, n_y, n_z) = (-\sin\phi\cos\theta, \cos\phi, \sin\phi\sin\theta)$

$$\boldsymbol{B}\cdot(\boldsymbol{n}_{GB}+\boldsymbol{n}_{GT}) = B_n^{GB}(V_{GB}) + B_n^{GT}(V_{GT})$$
$$\boldsymbol{B}\cdot(\boldsymbol{n}_{BB}+\boldsymbol{n}_{BT}) = B_n^{BB}(V_{BB}) + B_n^{BT}(V_{BT})$$
$$\boldsymbol{B}\cdot(\boldsymbol{n}_{RB}+\boldsymbol{n}_{RT}) = B_n^{RB}(V_{RB}) + B_n^{RT}(V_{RT})$$

$$\begin{pmatrix} n_{x,GB}+n_{x,GT} & n_{y,GB}+n_{y,GT} & n_{z,GB}+n_{z,GT} \\ n_{x,BB}+n_{x,BT} & n_{y,BB}+n_{y,BT} & n_{z,BB}+n_{z,BT} \\ n_{x,RB}+n_{x,RT} & n_{y,RB}+n_{y,RT} & n_{z,RB}+n_{z,RT} \end{pmatrix} \begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix} = \begin{pmatrix} B_n^{GB}(V_{GB}) + B_n^{GT}(V_{GT}) \\ B_n^{BB}(V_{BB}) + B_n^{BT}(V_{BT}) \\ B_n^{RB}(V_{RB}) + B_n^{RT}(V_{RT}) \end{pmatrix}$$

Design implications

- Planar Hall effect and loop-induced voltage compensation



$$V_{PH} = \frac{R_{PH}}{2t} I B_p^2 \sin 2\theta$$

if $R_{PH1} = R_{PH2}, B_{p1} = B_{p2}, |\theta_2 - \theta_1| = 90^\circ$:

$$\boxed{\frac{1}{2}\left(V_{PH1} + V_{PH2}\right) = 0}$$

I direction (orthogonal): PHE compensation

I direction (+ or -): induced voltage compensation

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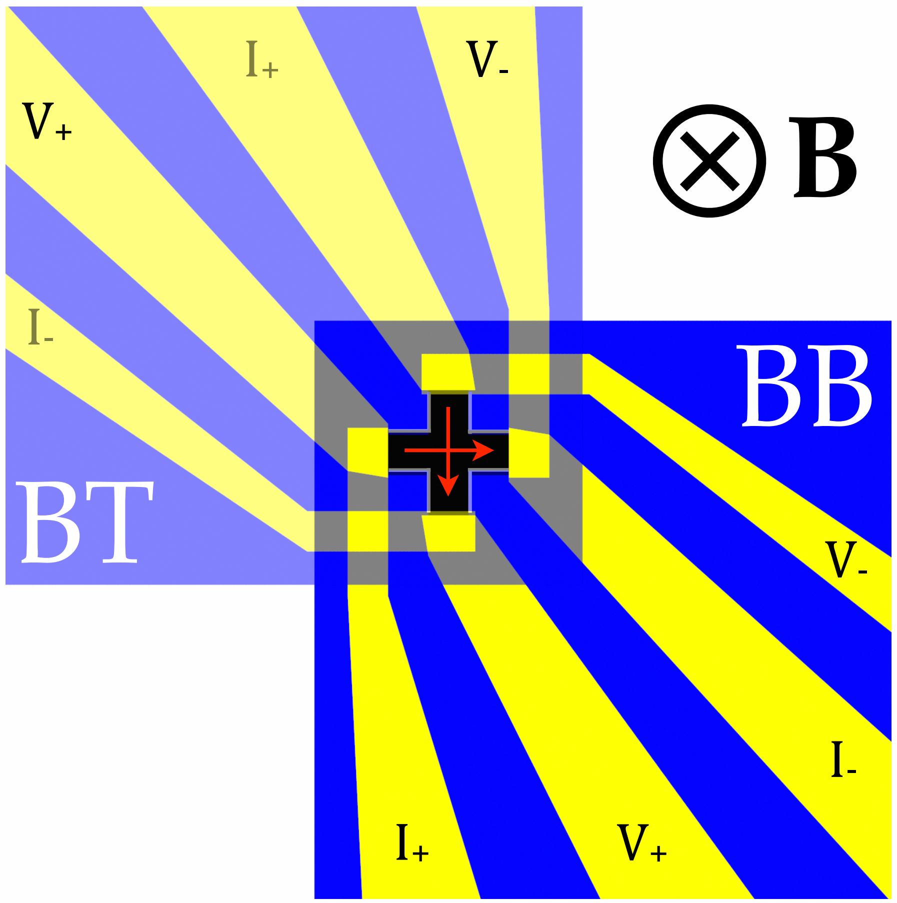

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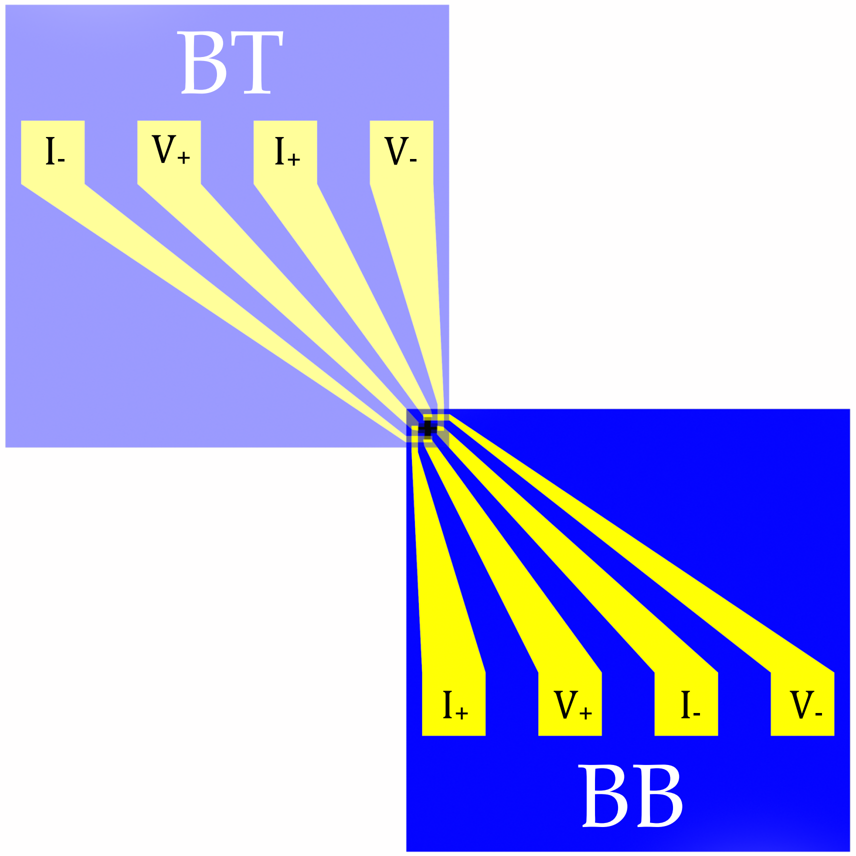

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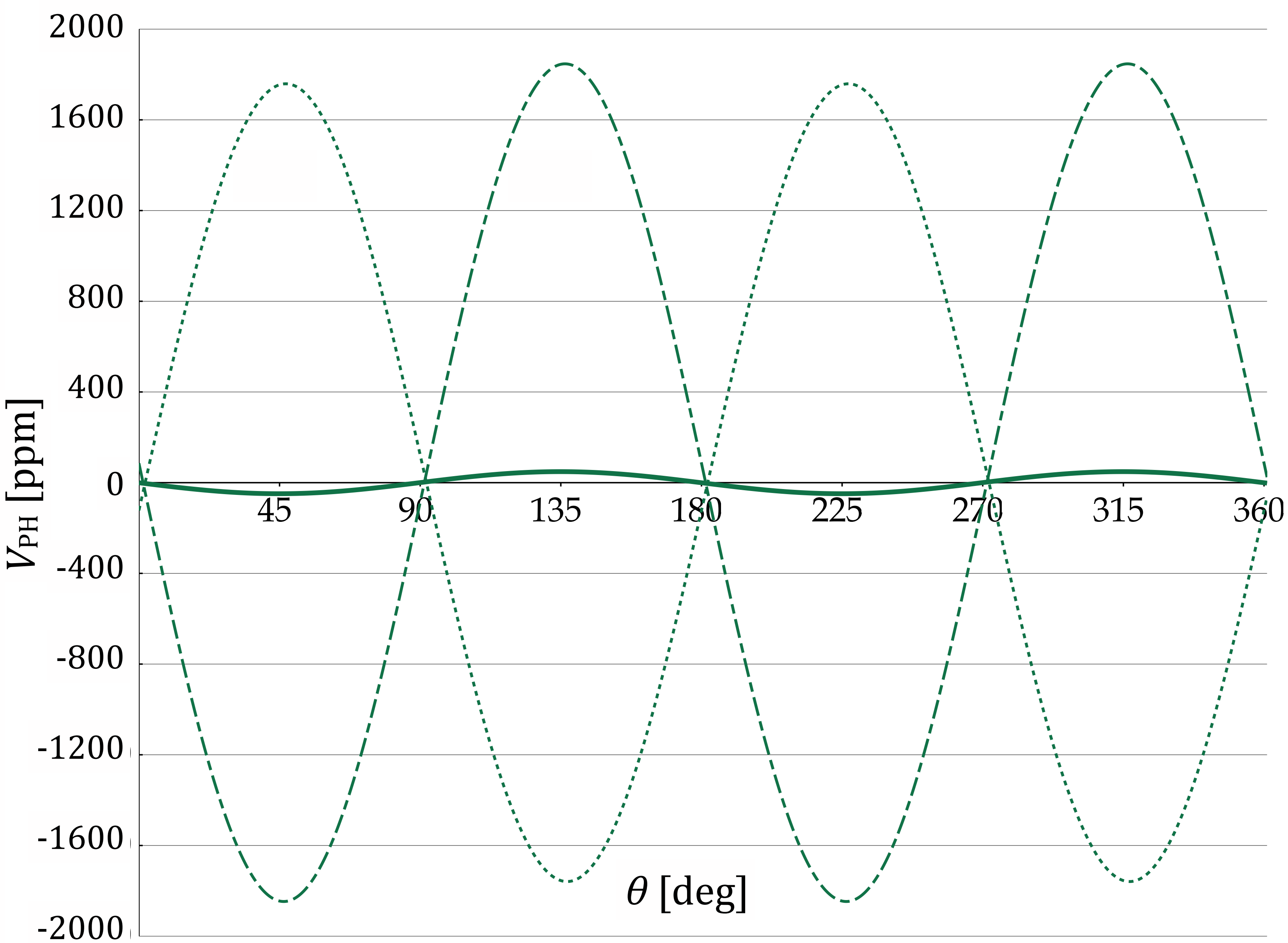
if $\left|\theta_2 - \theta_1\right| \neq 90^\circ$: per degree angular error, 1.7% of the PH voltage is not cancelled out

if $R_{PH1} \neq R_{PH2}$: for 1% difference, 0.5% of the PH voltage is not cancelled out

if $B_{p1} \neq B_{p2}$: for 1% difference, also 1% of the PH voltage is not cancelled out

Planar Hall effect voltage compensation



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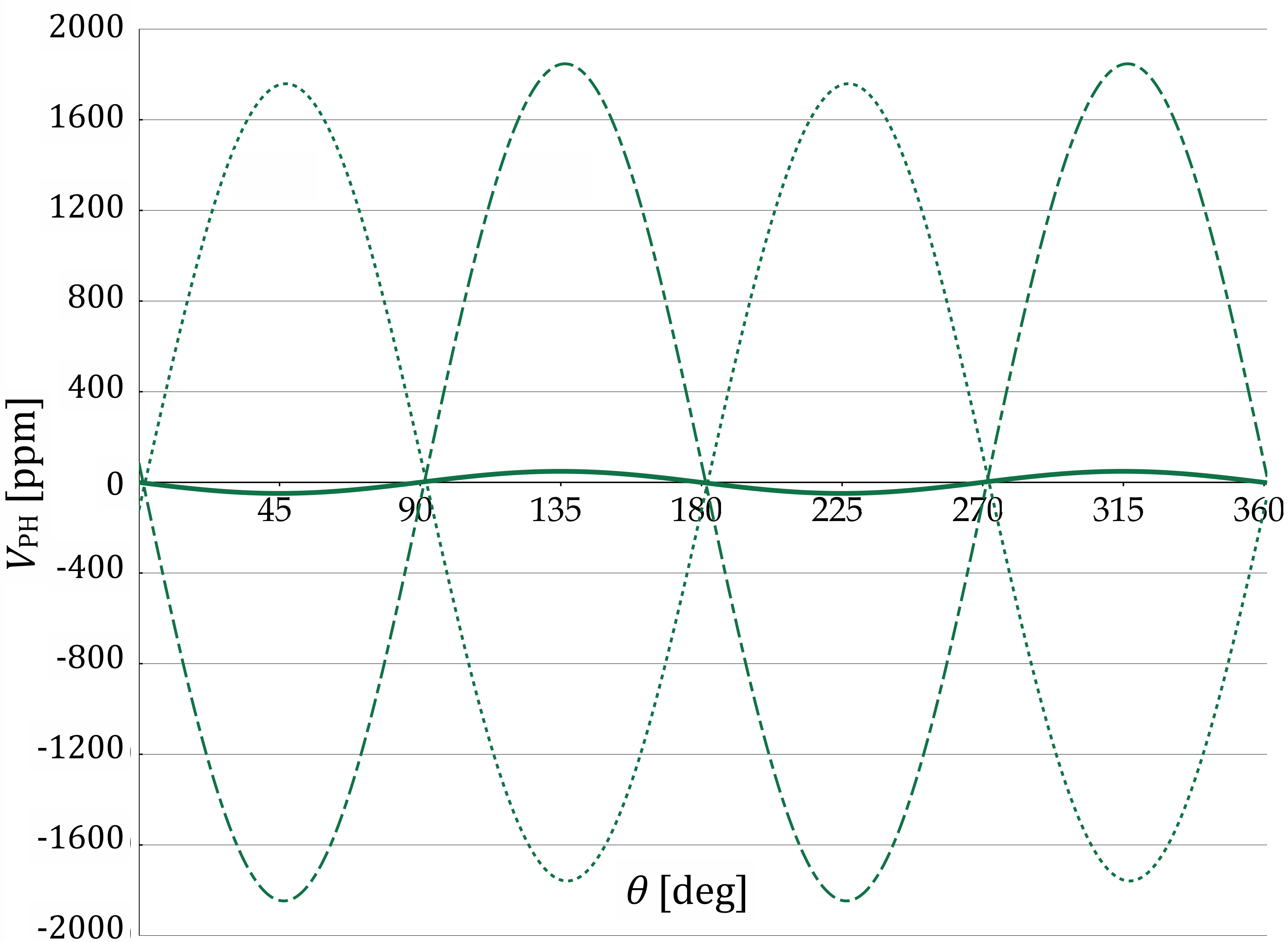

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$$B_p = 1\mathrm{T}$$

- Planar Hall effect 500-600 times weaker than Hall effect
- Reduced >35 times by compensation using pairs
- Remnant maximum V_{PH} at 1 T is <5 µV (or 50 ppm) for worst pair → 0.5 Gauss max err.

Total field reconstruction

- Goal: target accuracy: <100 ppm at the 1 T level for *any* magnetic field direction

Homogeneous magnetic field volume

- Known field (NMR probe)
- Total measured field, $B_{\text{mod}} = \sqrt{B_x^2 + B_y^2 + B_z^2}$, should be constant
- Even if not $\alpha \perp \beta$ and not $\boldsymbol{B} \perp \alpha$
- Calibration magnet at 1 T: At every β position preform 360° rotation around α

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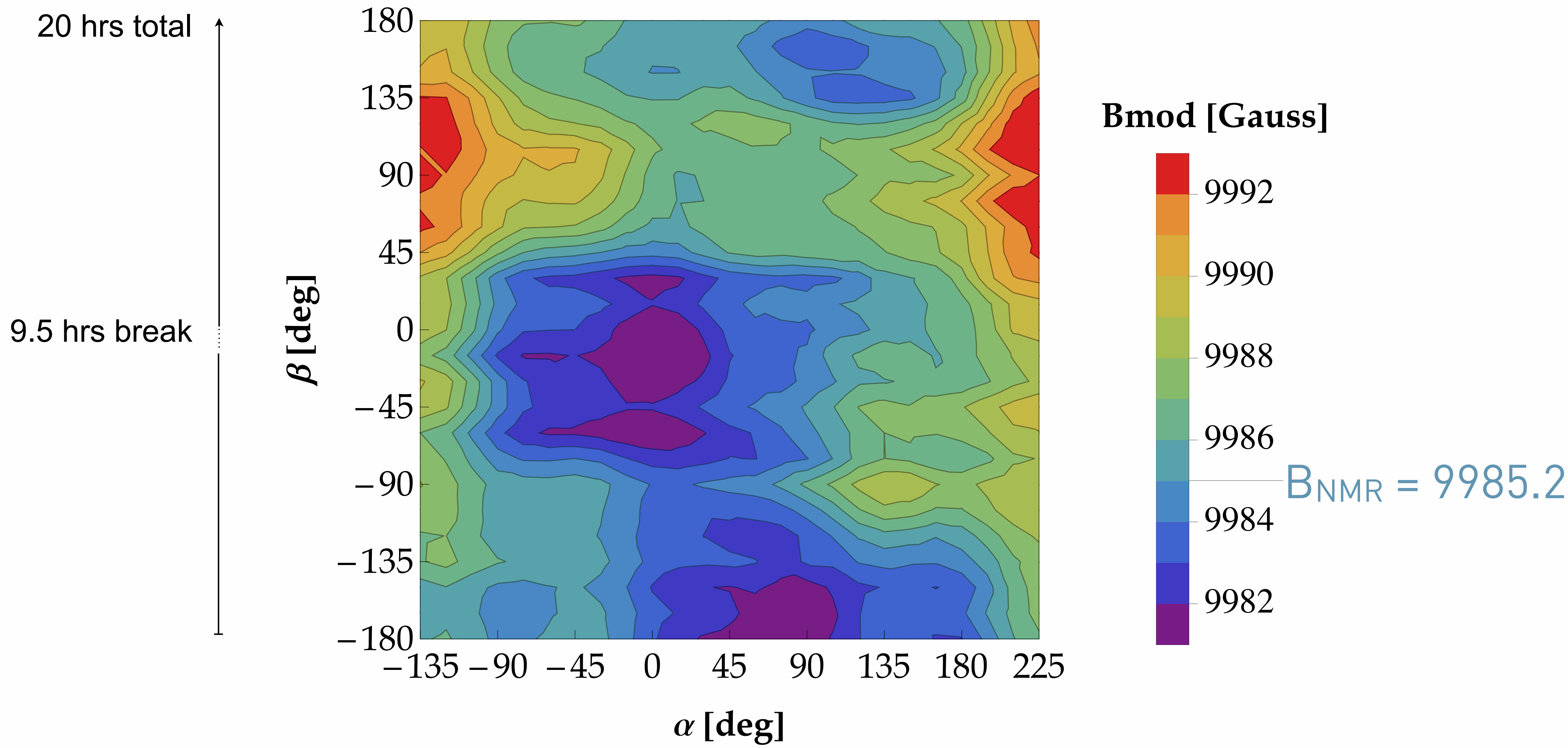
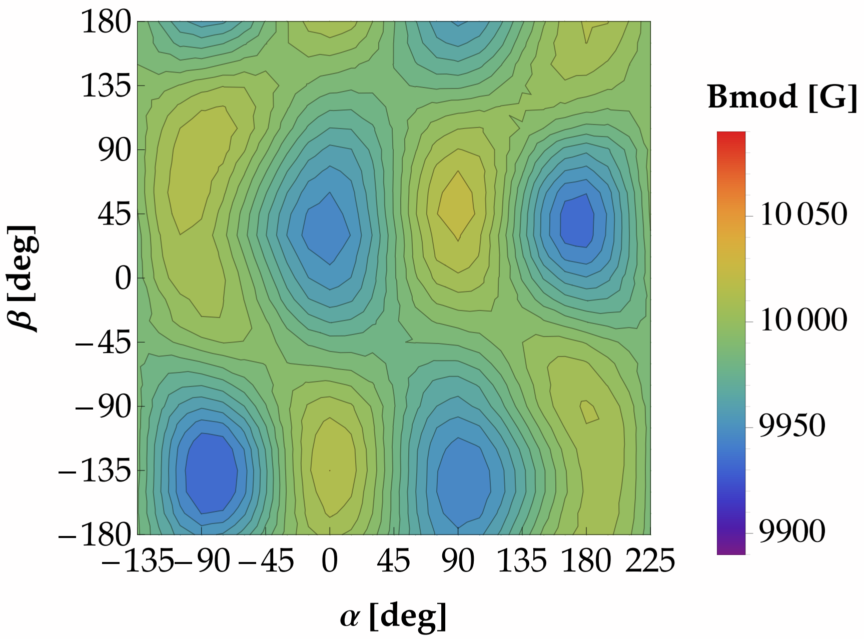
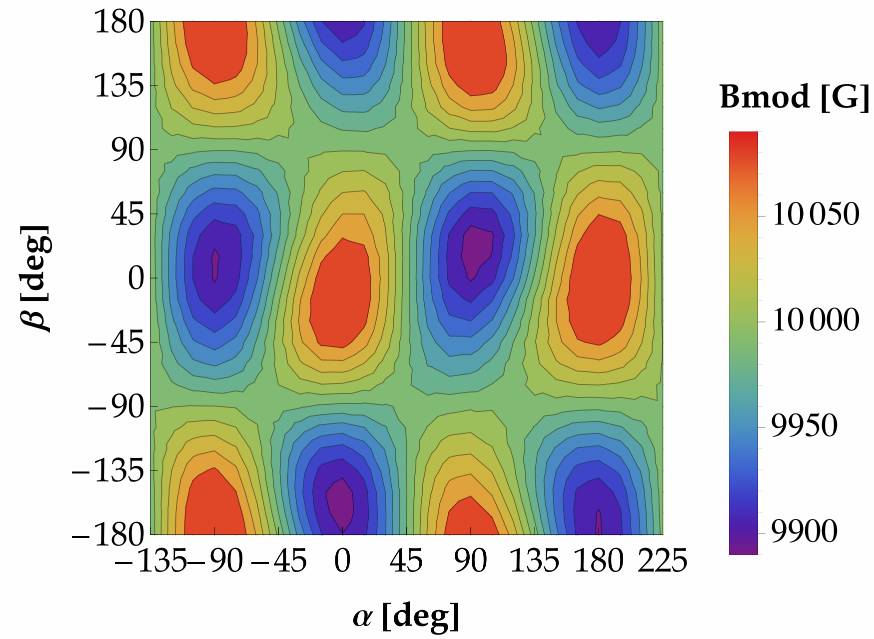


Total field reconstruction for full α and β rotation in a homogeneous field of 1 T, pp = 12 Gauss

Total field reconstruction



Total field reconstruction from BT, GB, and RT Hall sensors without angular error correction, pp = 88 G



Total field reconstruction from BB, GT, and RB Hall sensors without angular error correction, pp = 189 G

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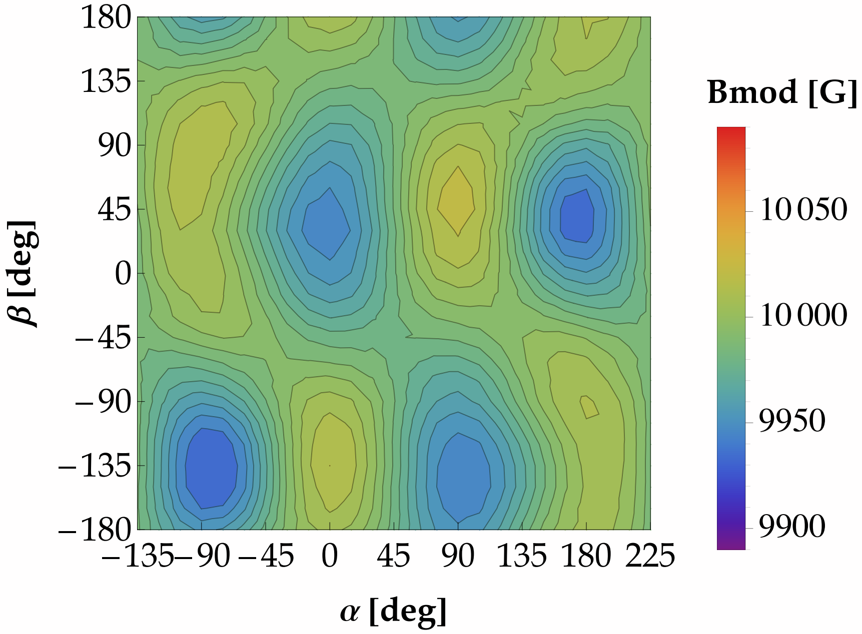

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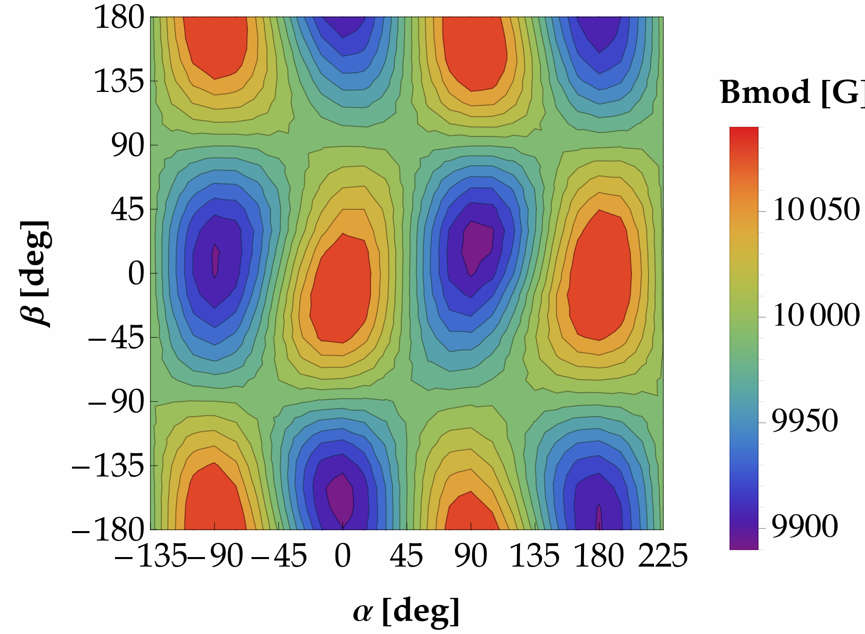

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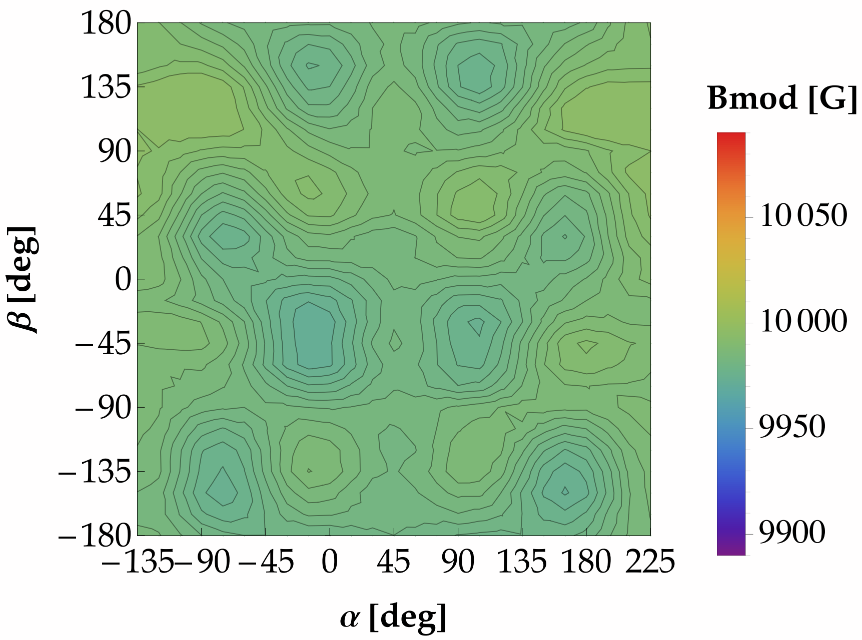
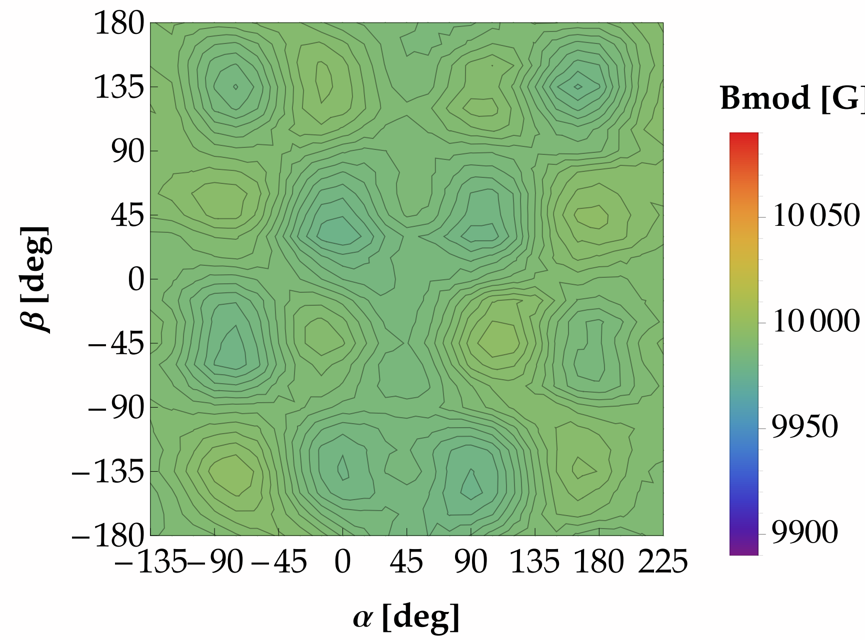


Total field reconstruction from BT, GB, and RT Hall sensors with angular error correction, pp = 23 G



Total field reconstruction from BB, GT, and RB Hall sensors with angular error correction, pp =21 G

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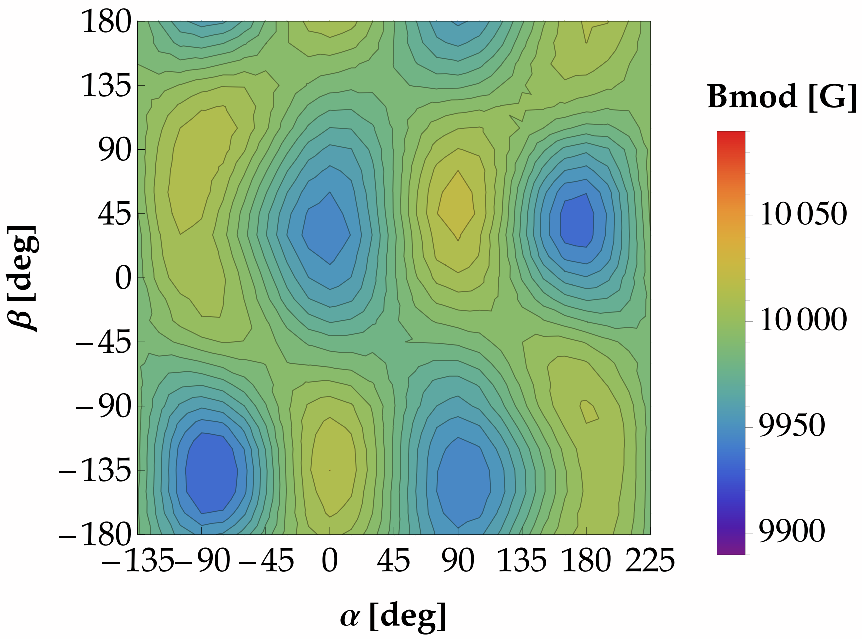

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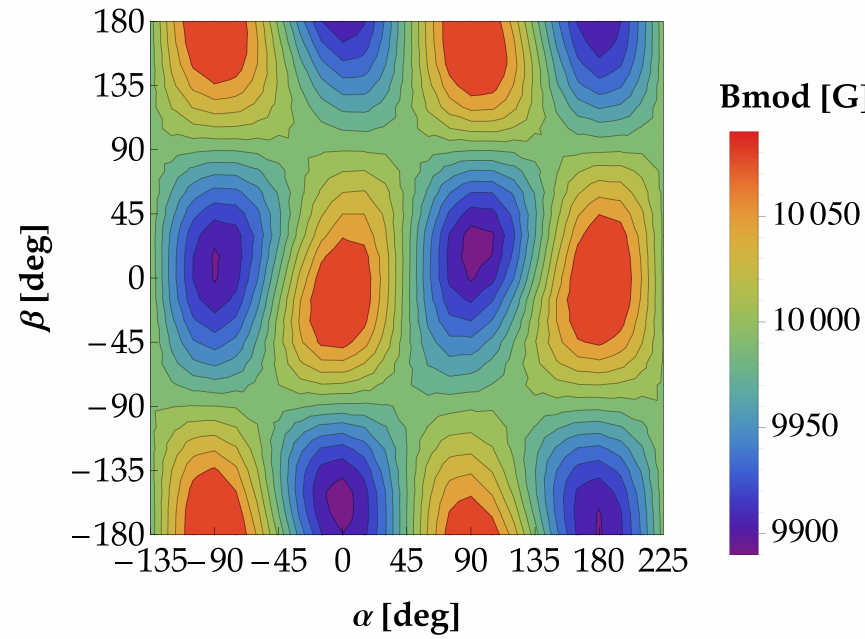

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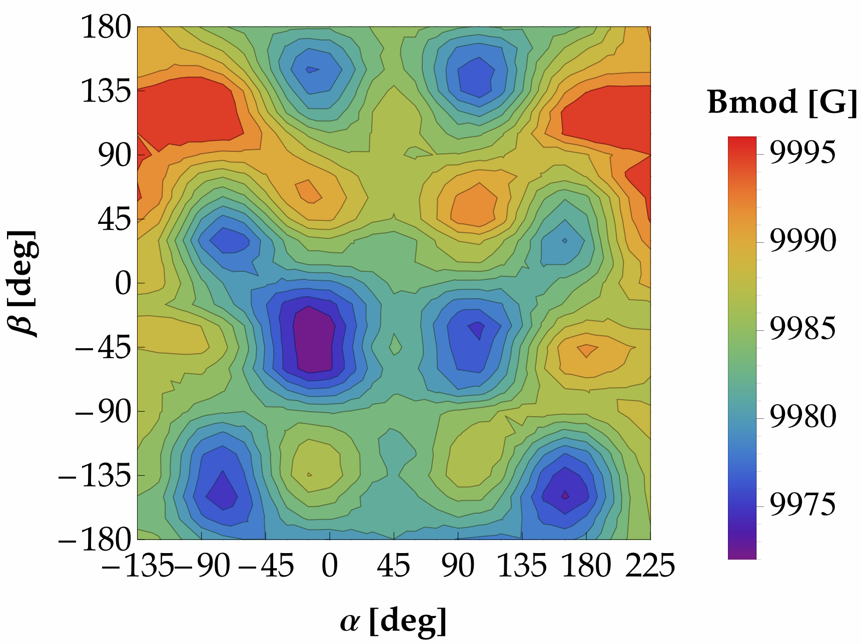

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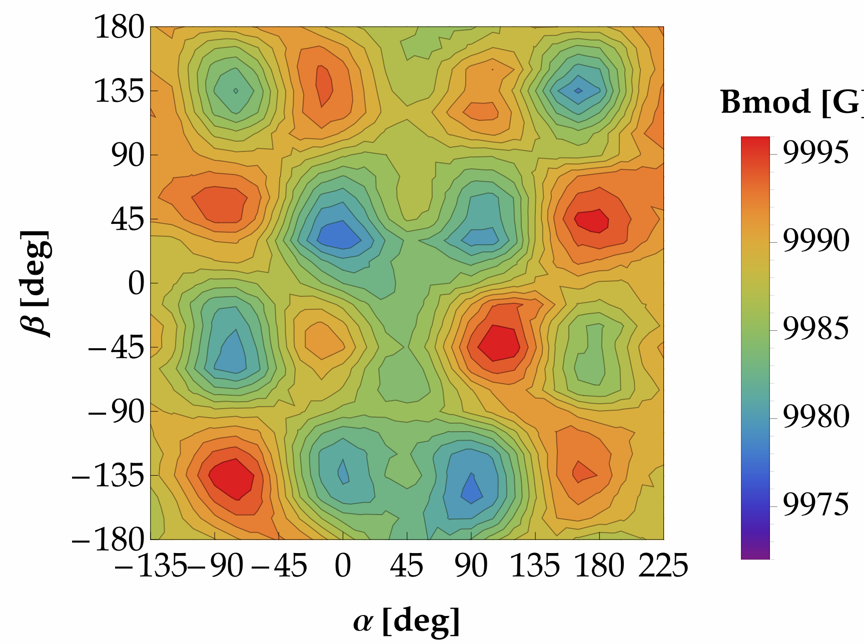

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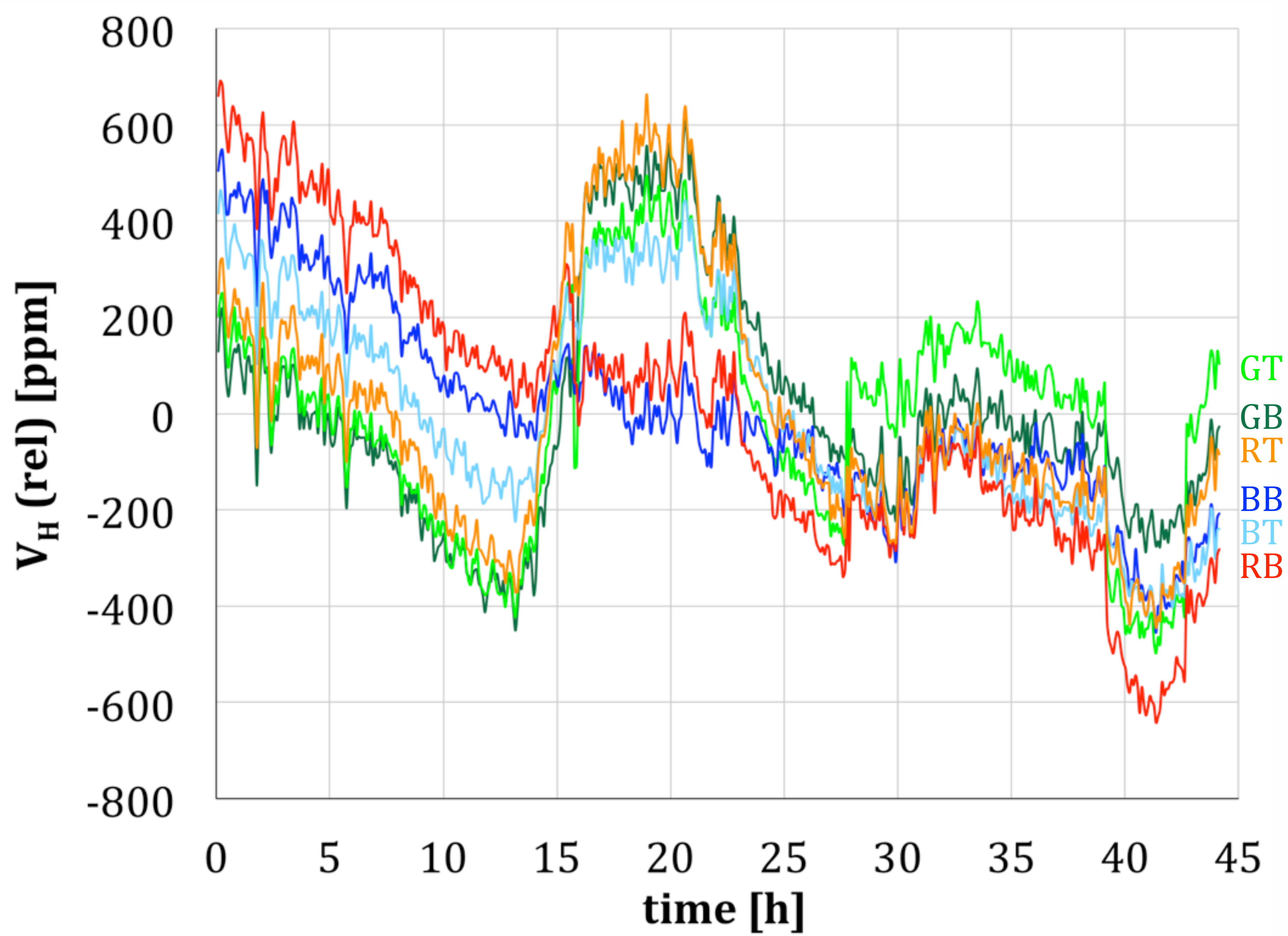
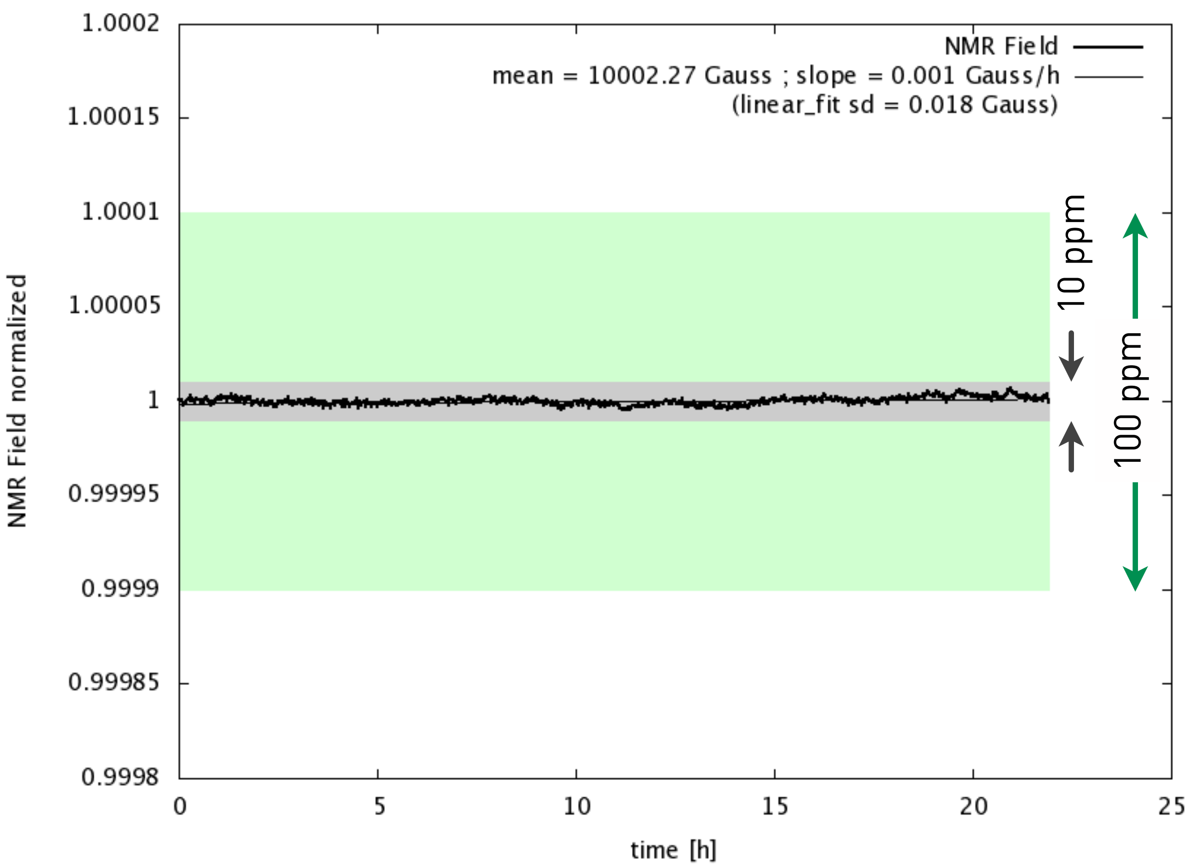
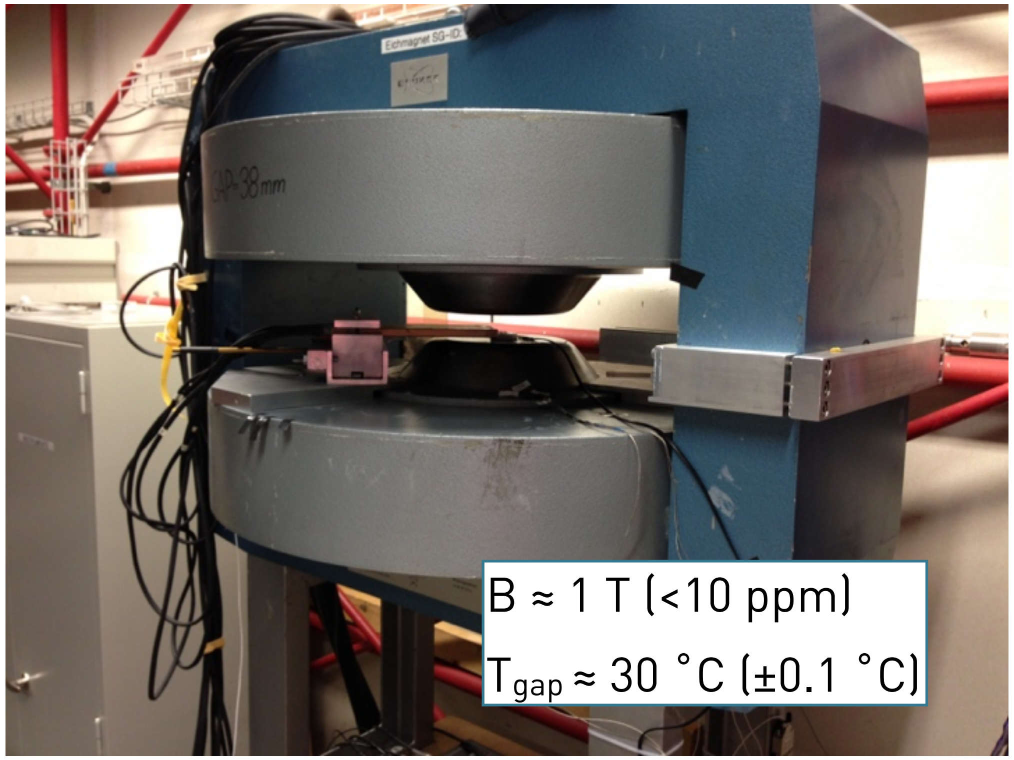
Long-term stability

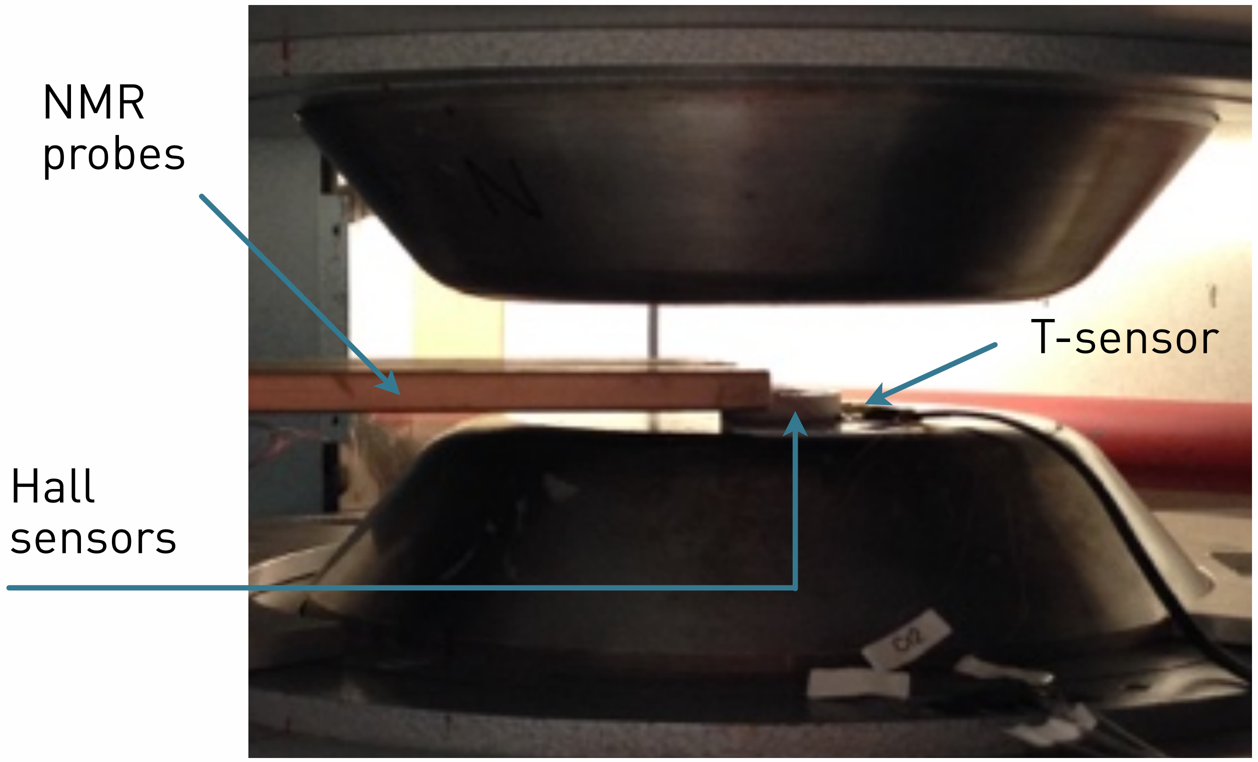


Measurement setup

- Long-term measurements: every 60 s one data point (avg of 100 samples)
- V_H: HP/Agilent/Keysight 3458A
- I_H: 1.0 mA DC, series, Keithley 6221
- NMR probes: Metrolab, PT2025
- Devices controlled over EPICS via Python script







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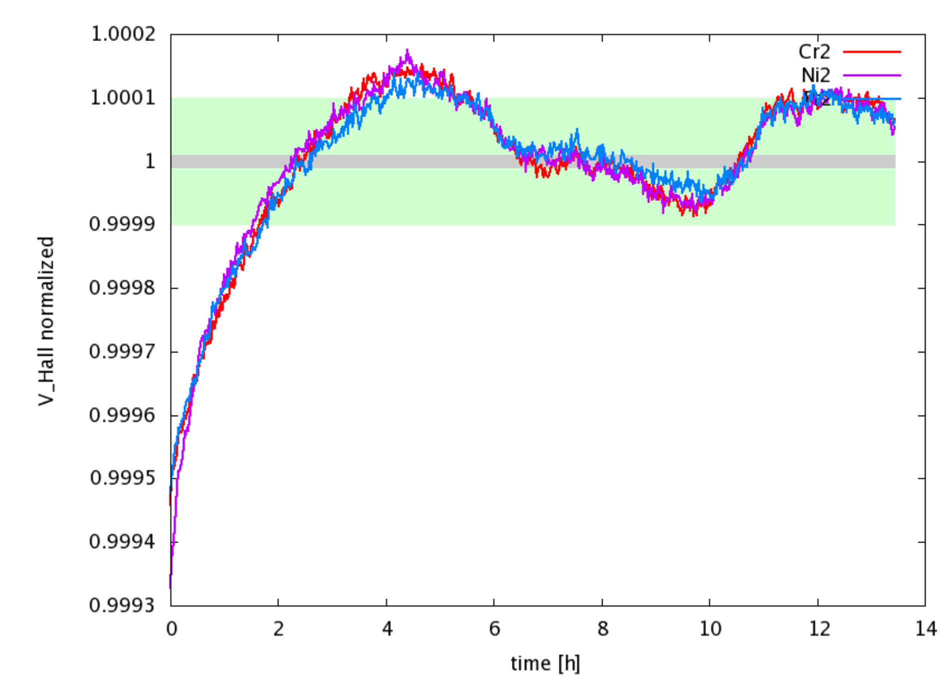

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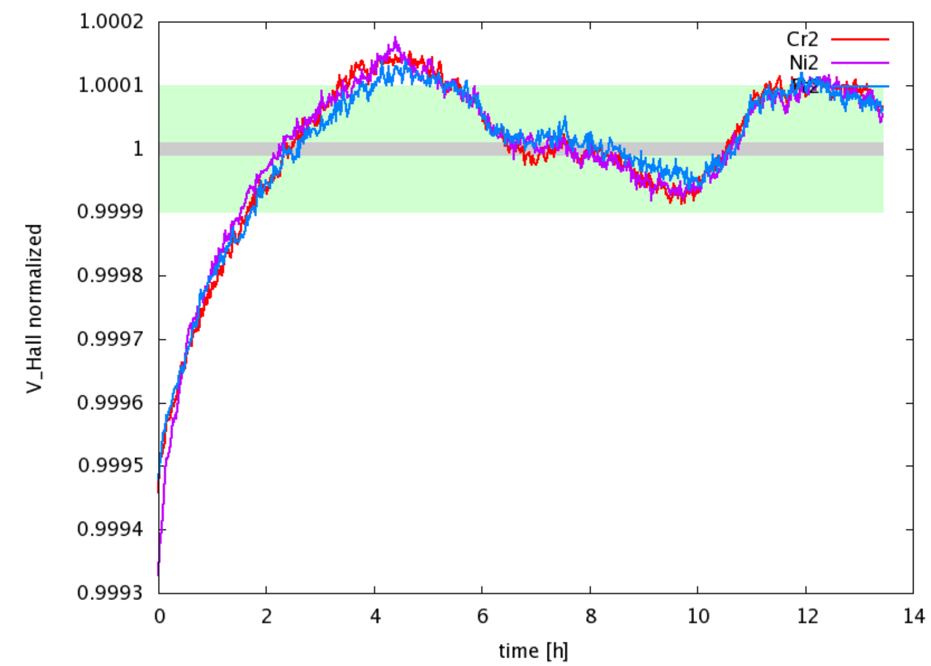

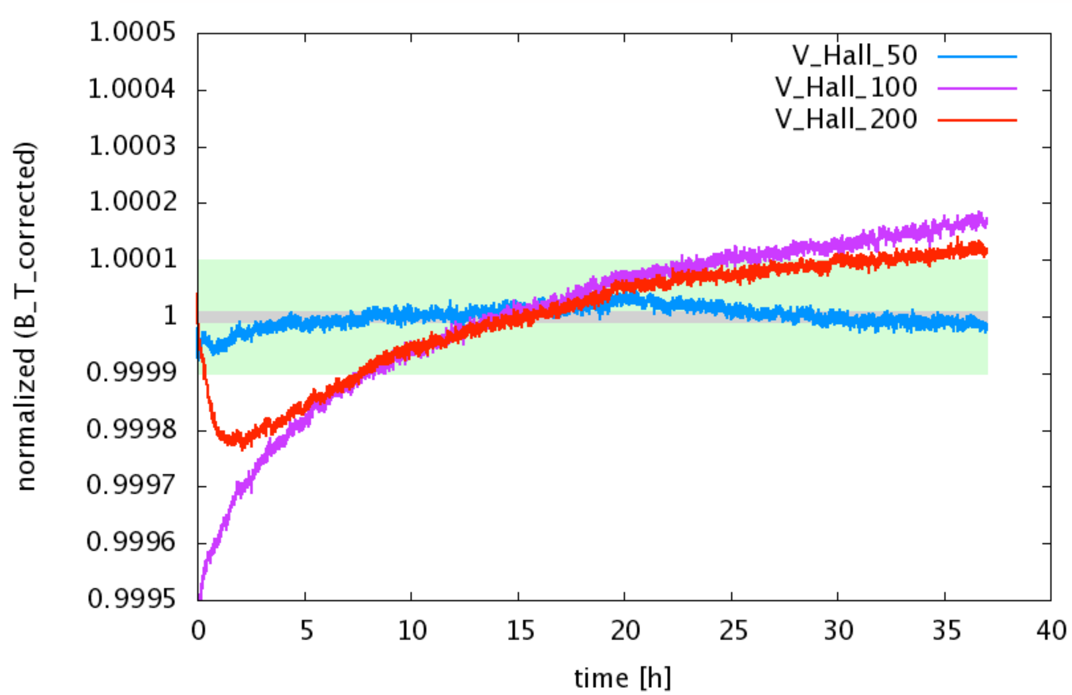

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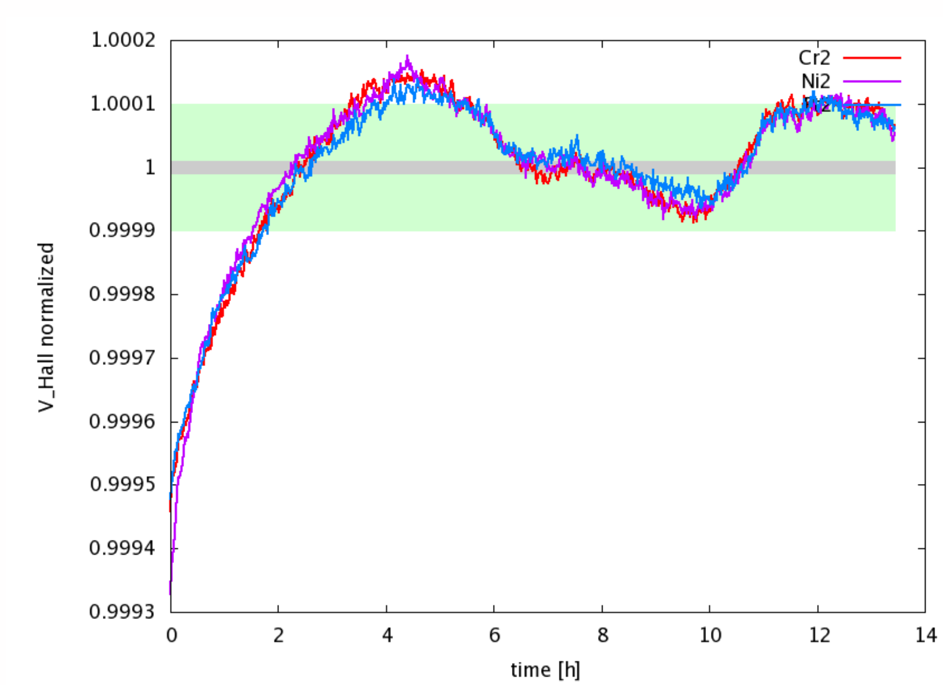

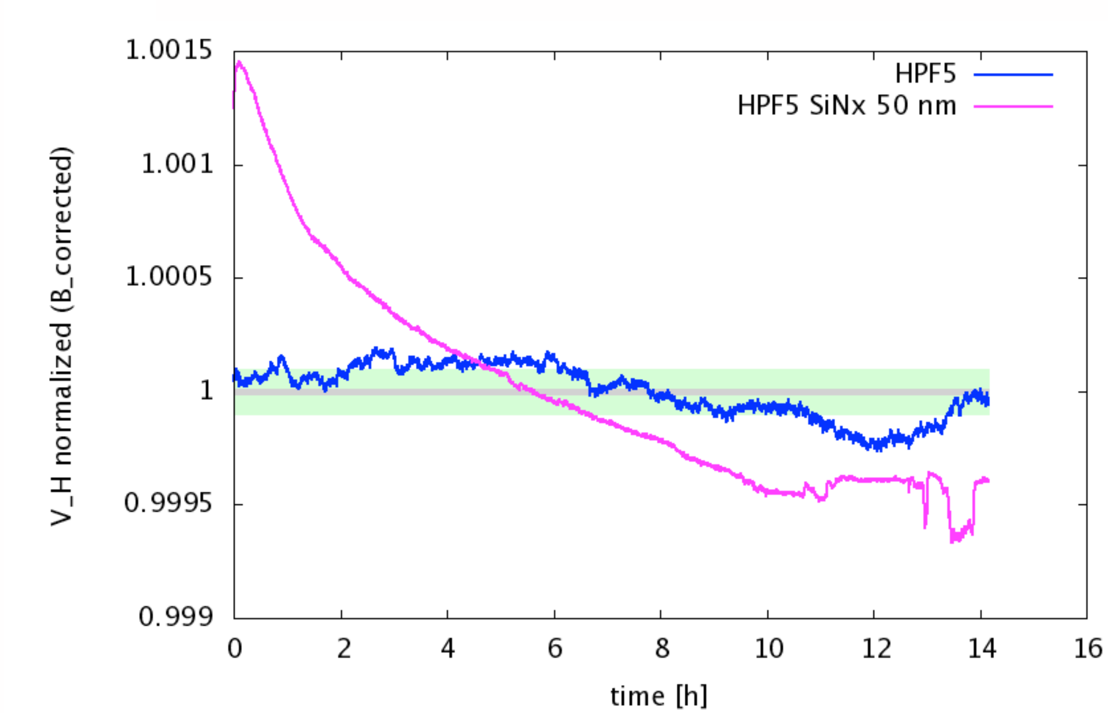

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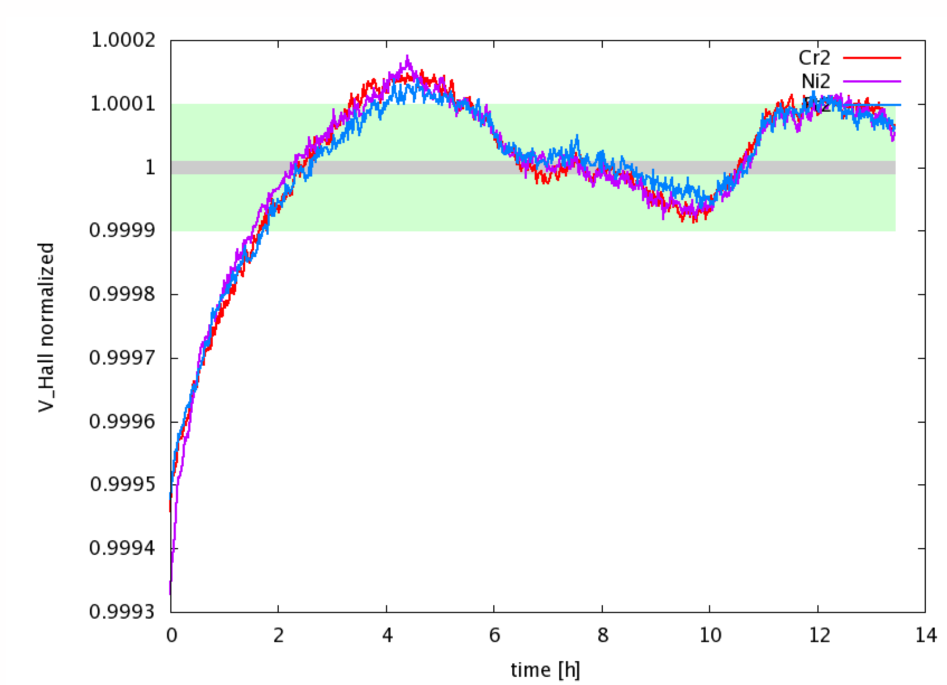
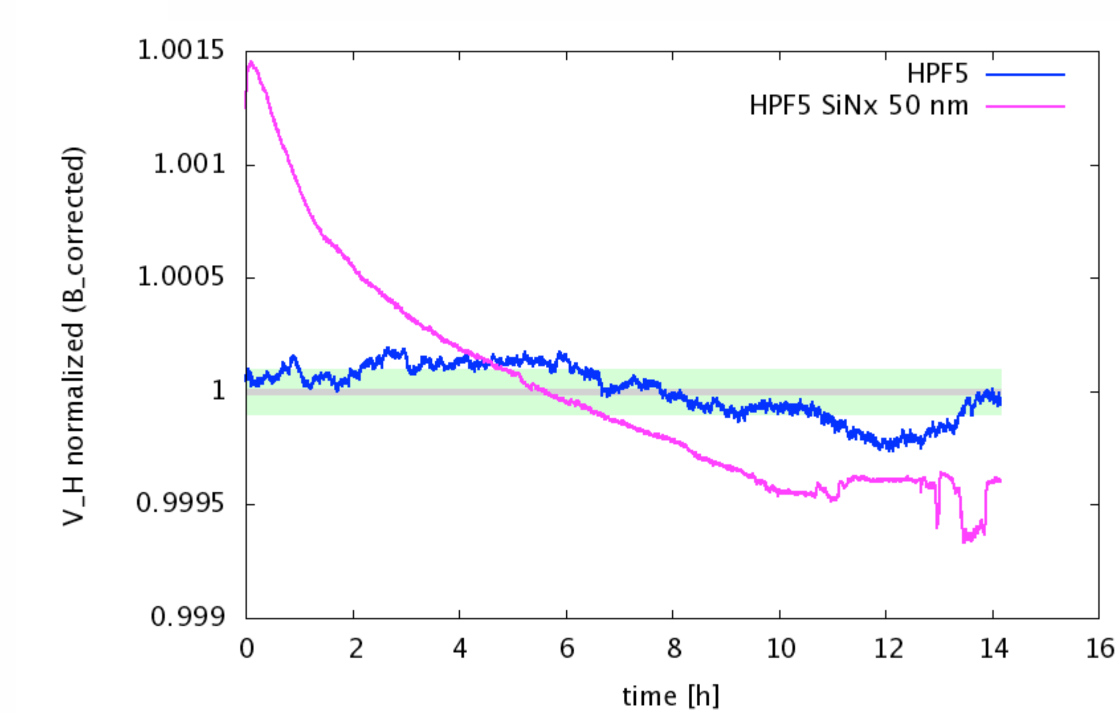
Cause?
Material, fabrication process, ~~measurement~~ setup





First results

Learned:

- Ohmic contact type (Ni, Ge, Cr) is not explanation for Hall voltage fluctuations.
- Best results obtained for:
  - remove GaAs cap layer (10 - 20 nm)
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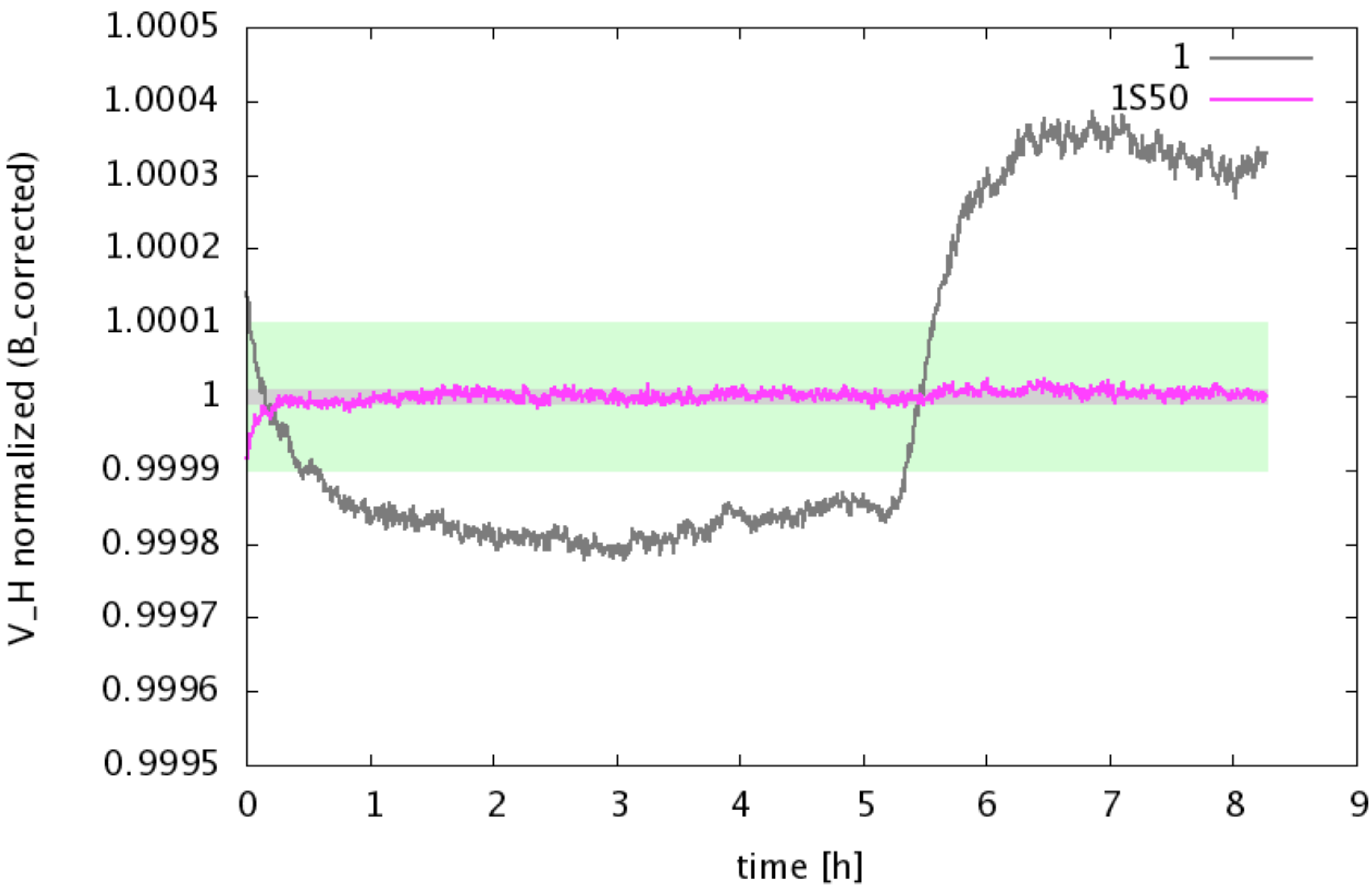
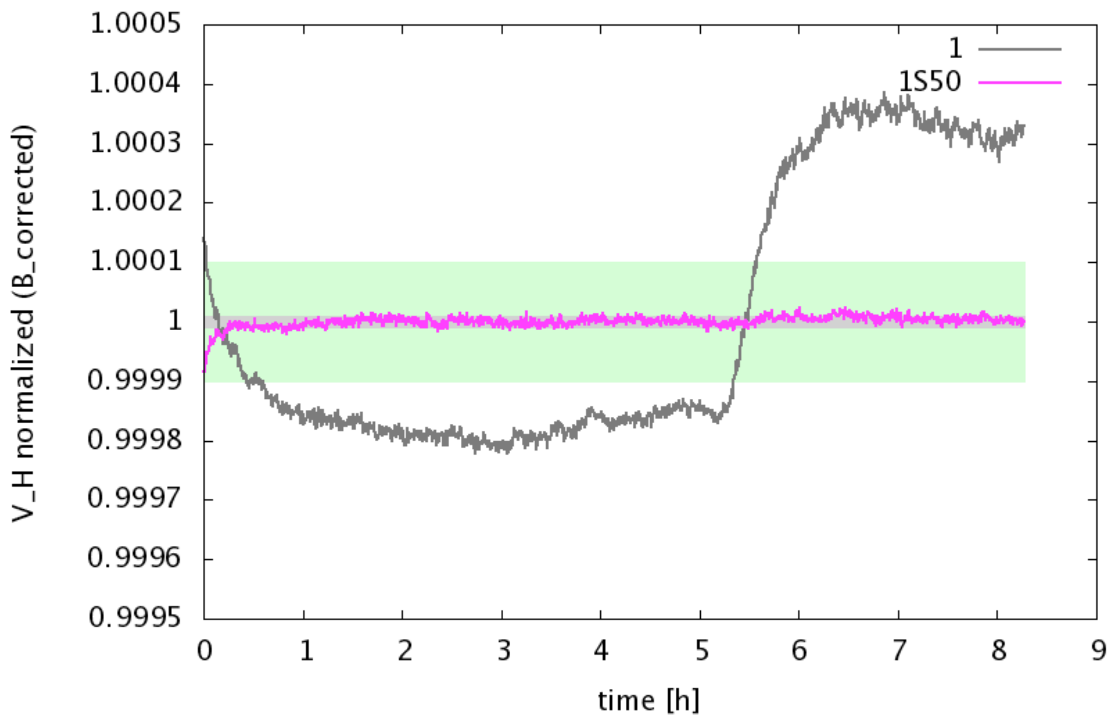
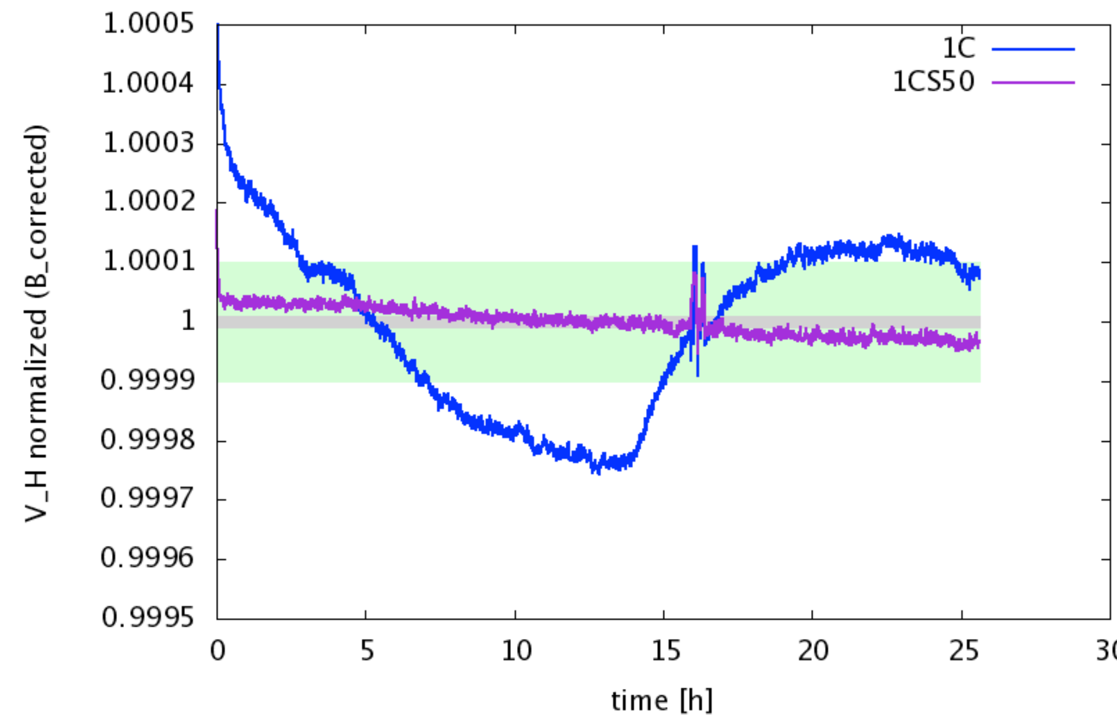
- Change material, cruciform dimensions

Effect of intact SiN_x passivation



GaAs cap layer/no cap layer





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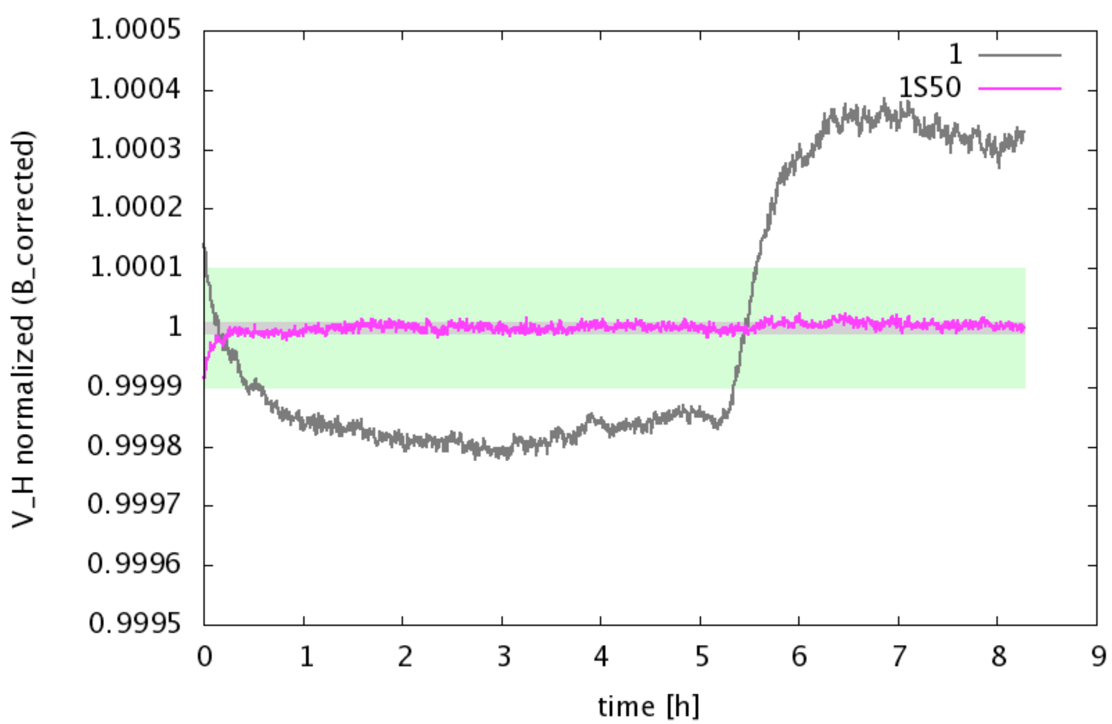
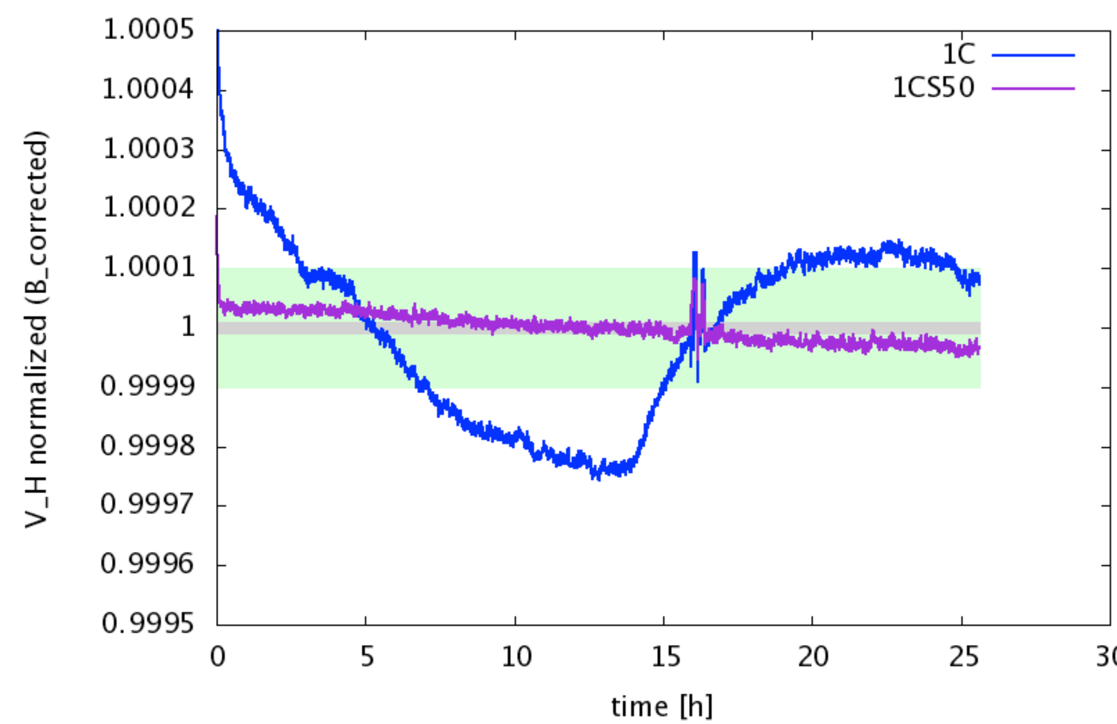
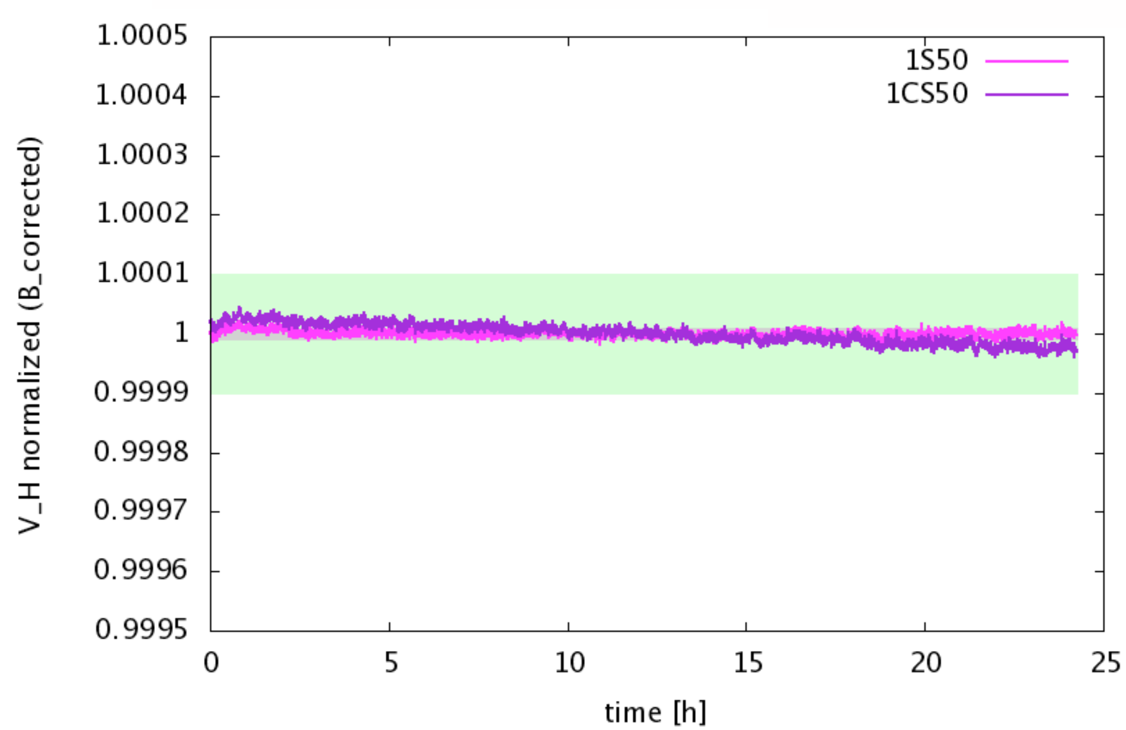
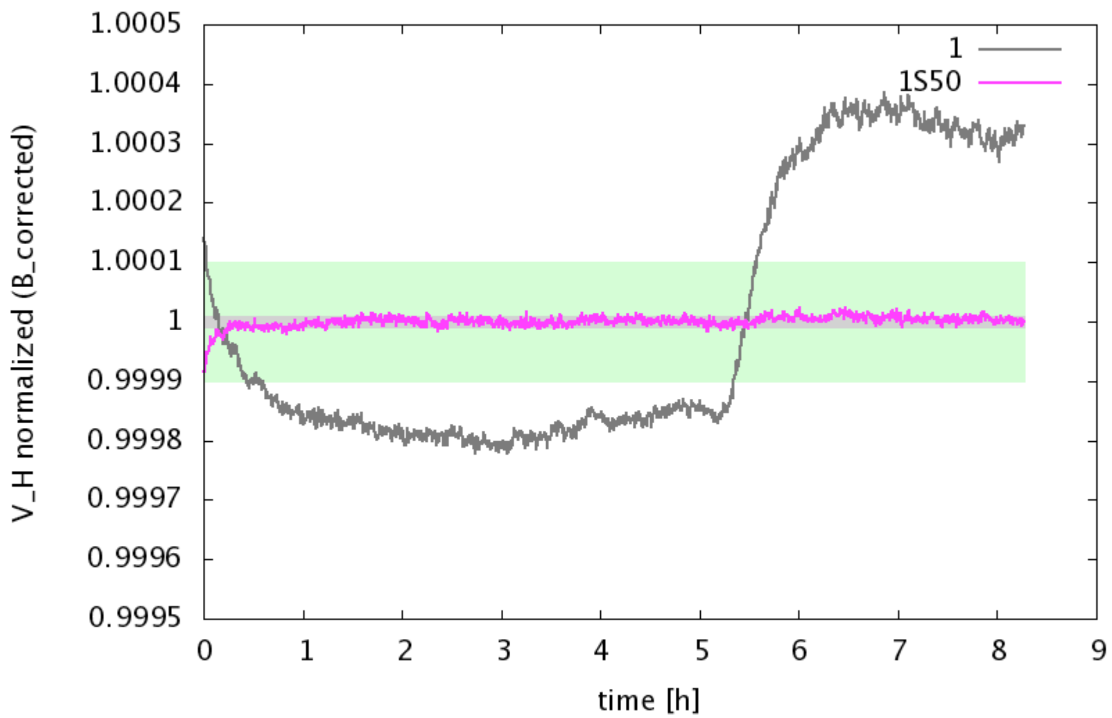
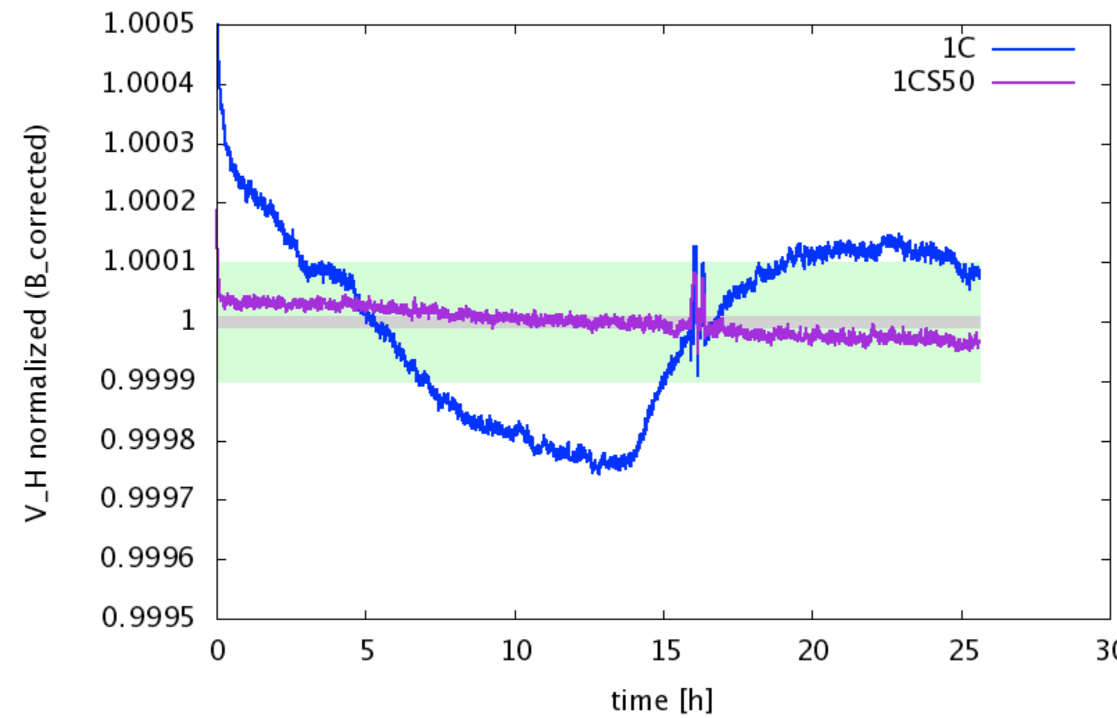


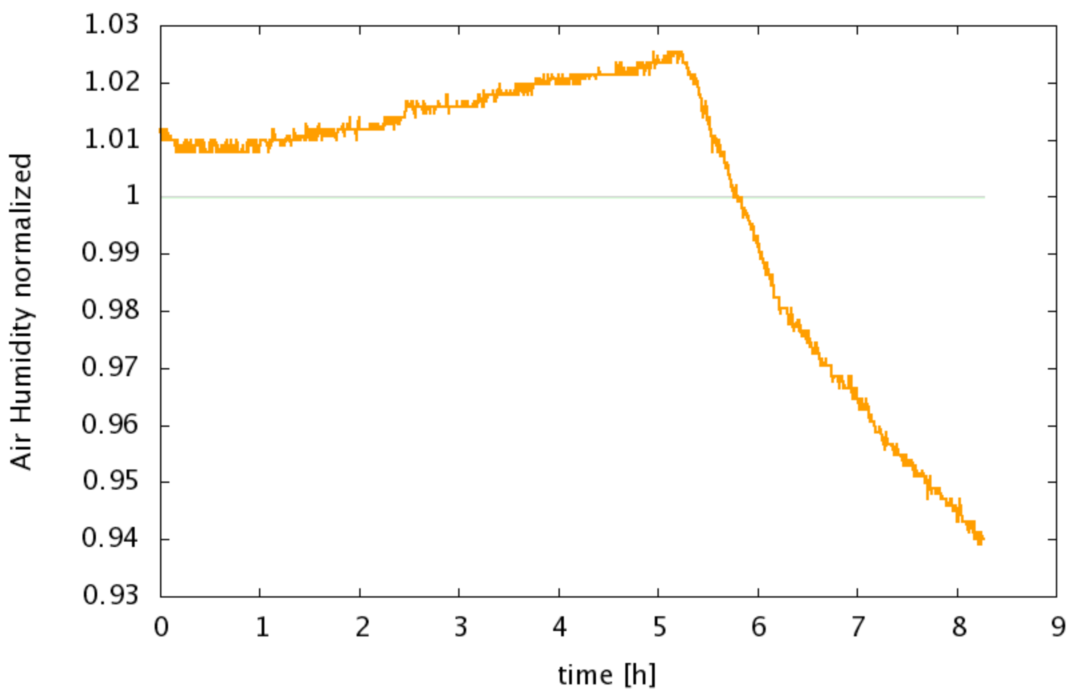


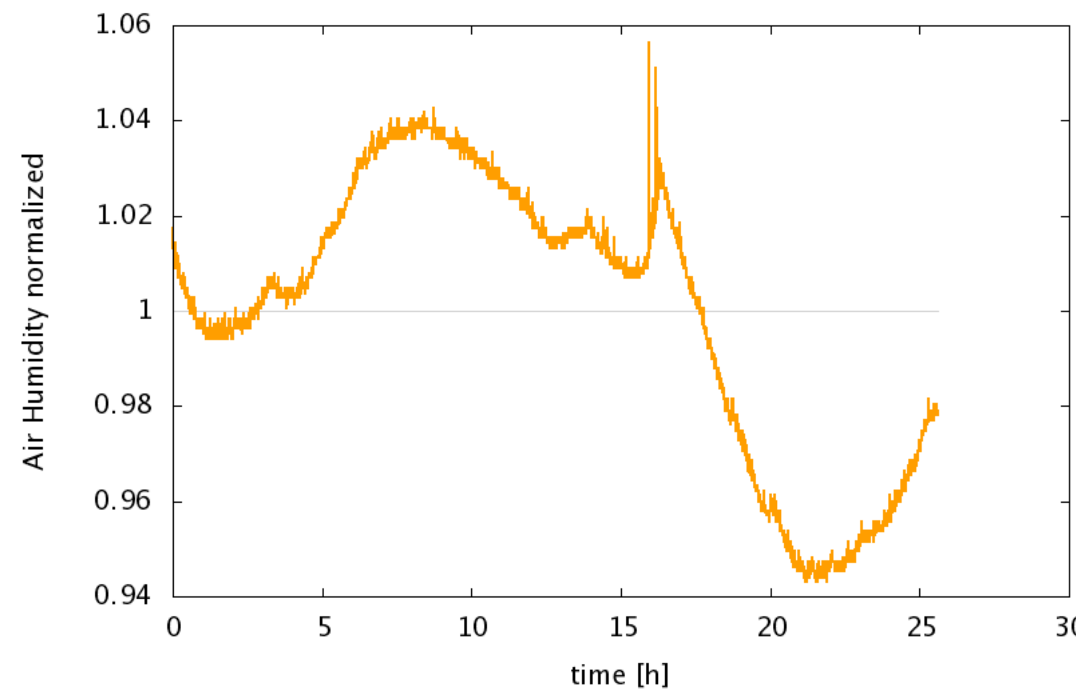


Humidity effect?









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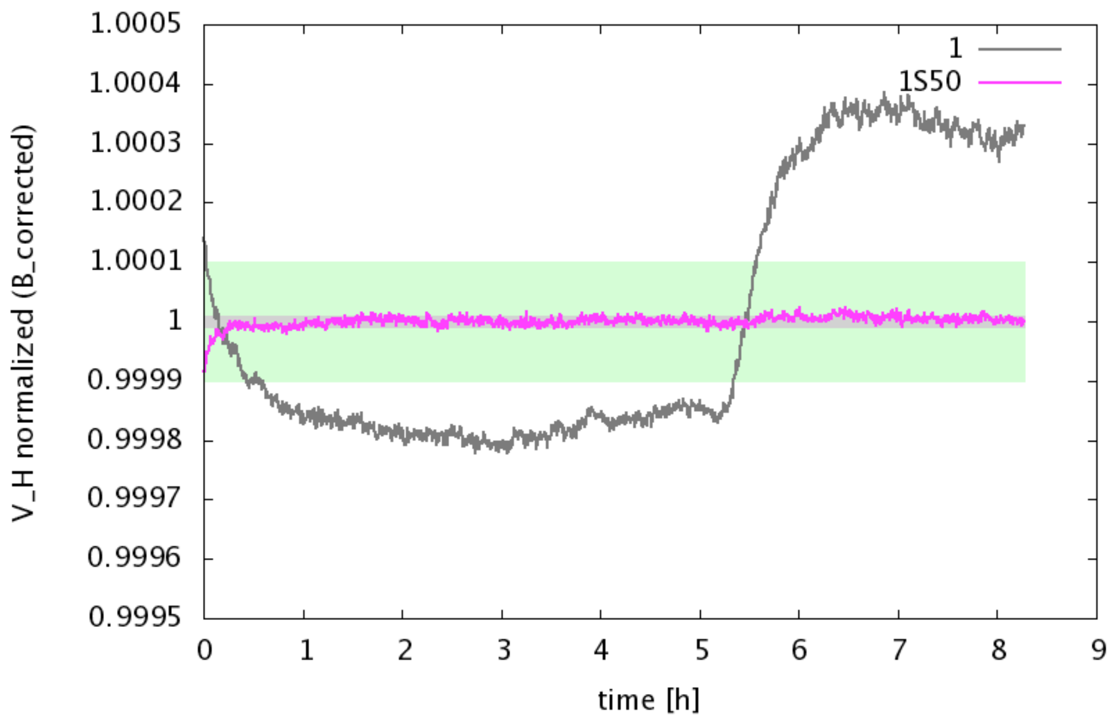

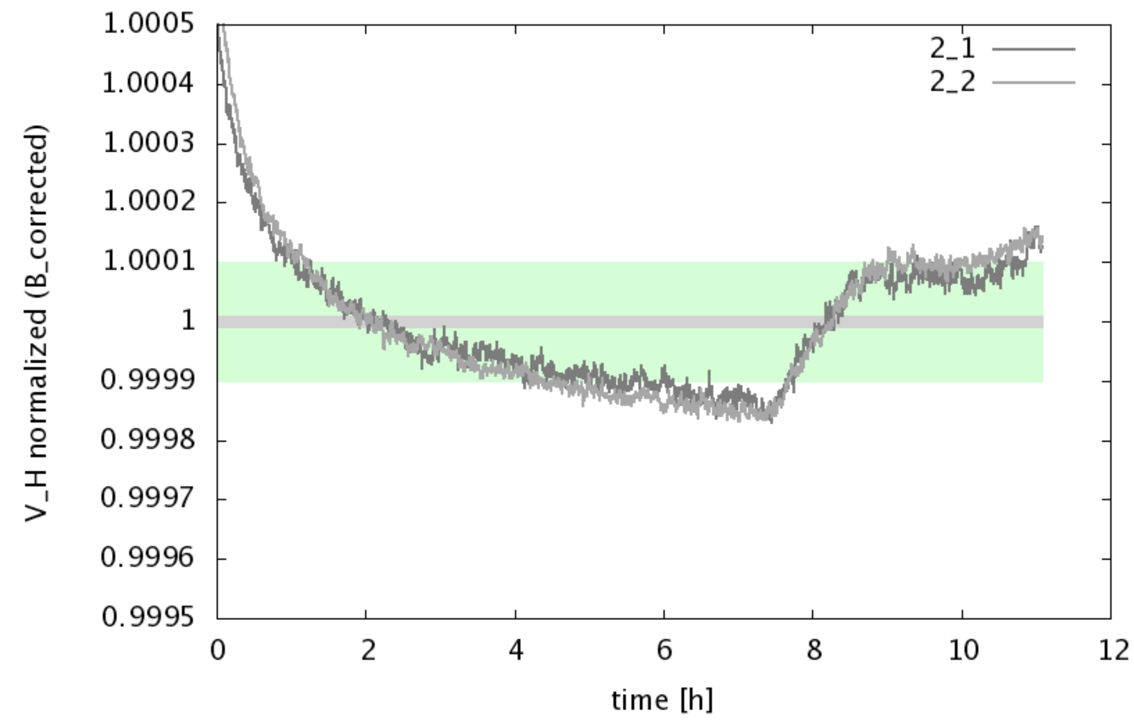

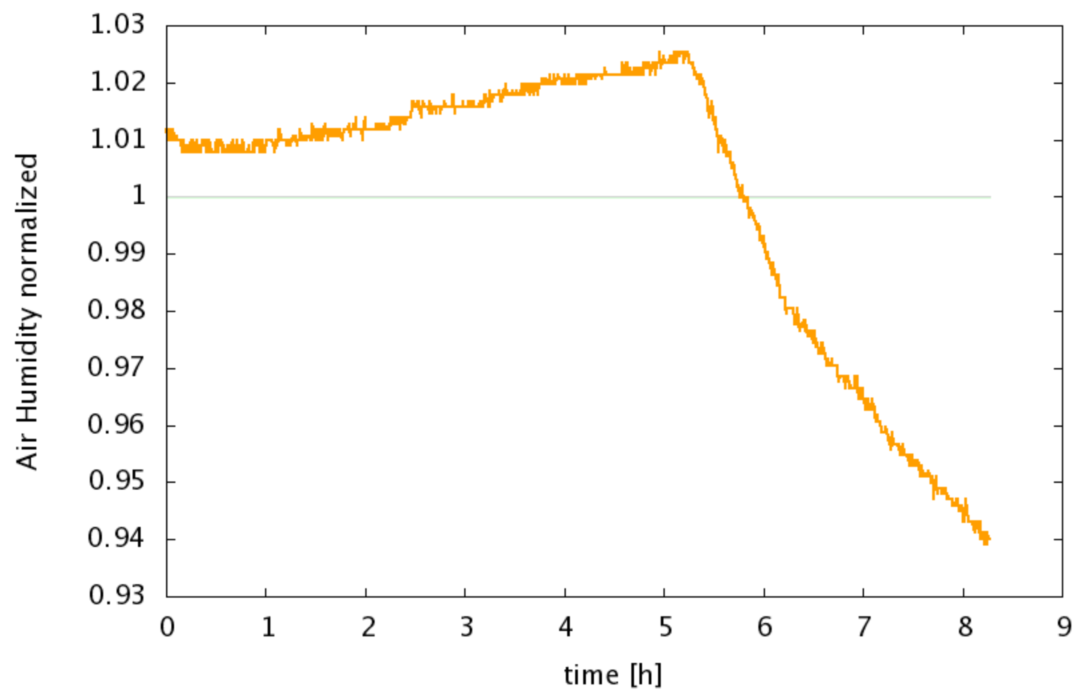

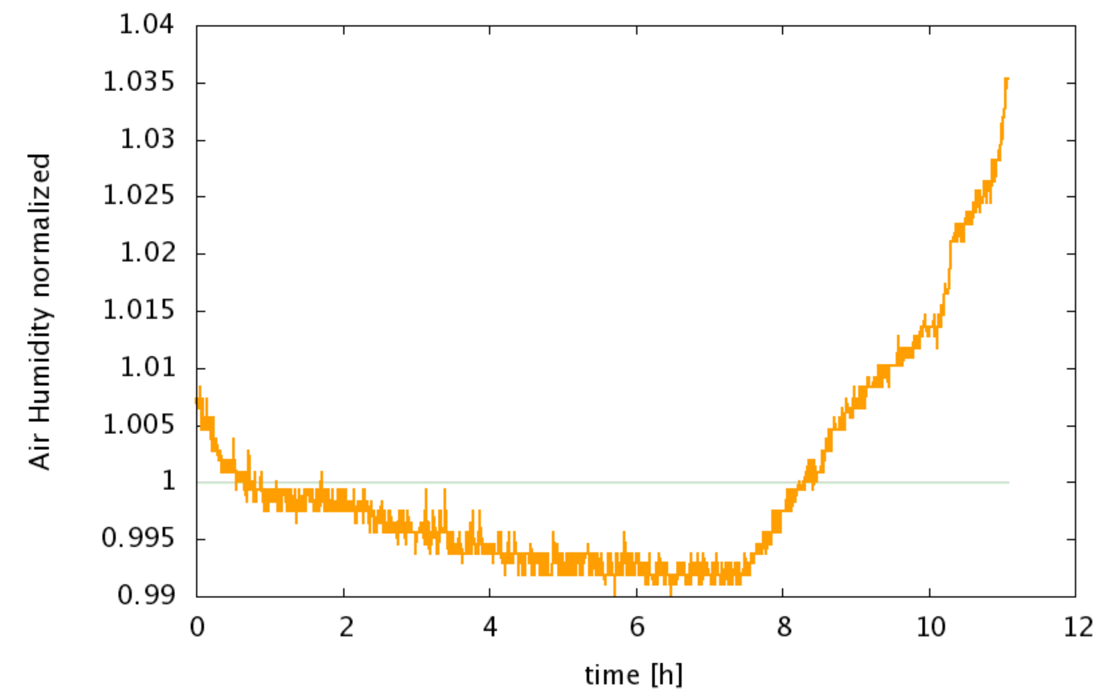

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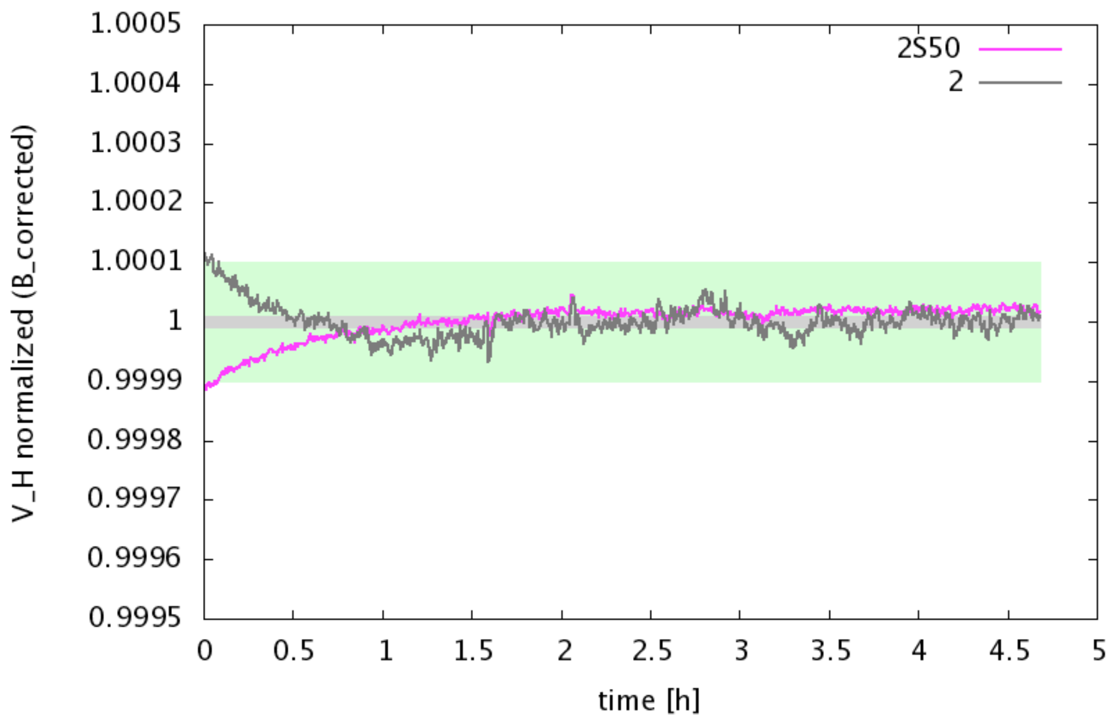
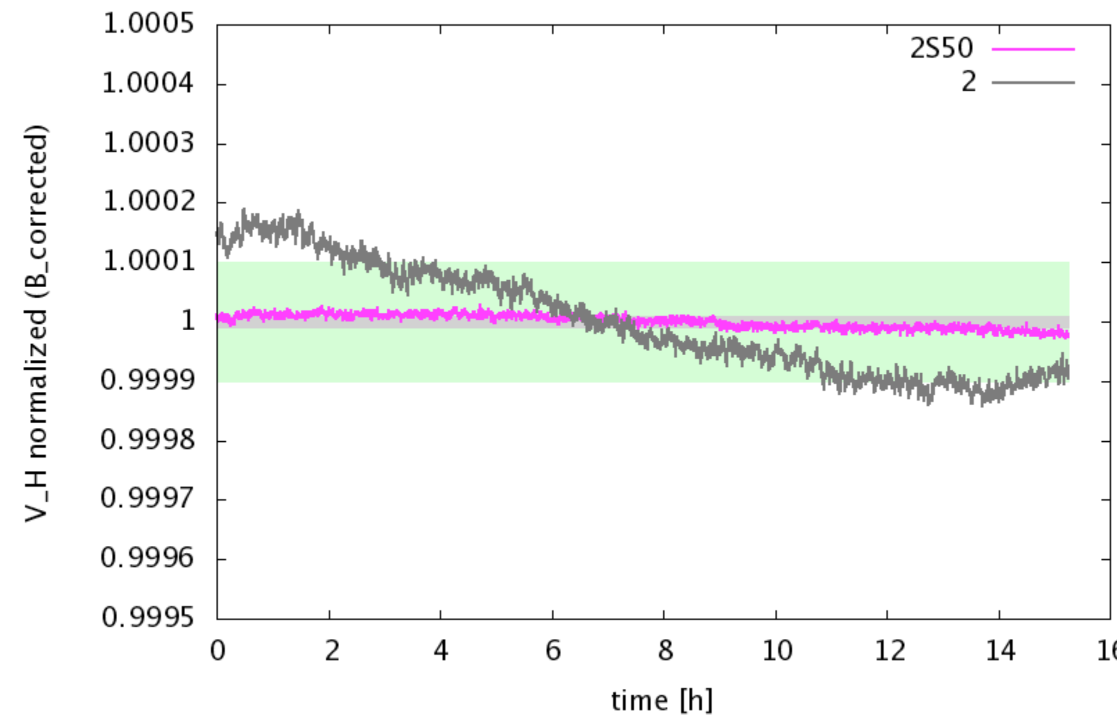
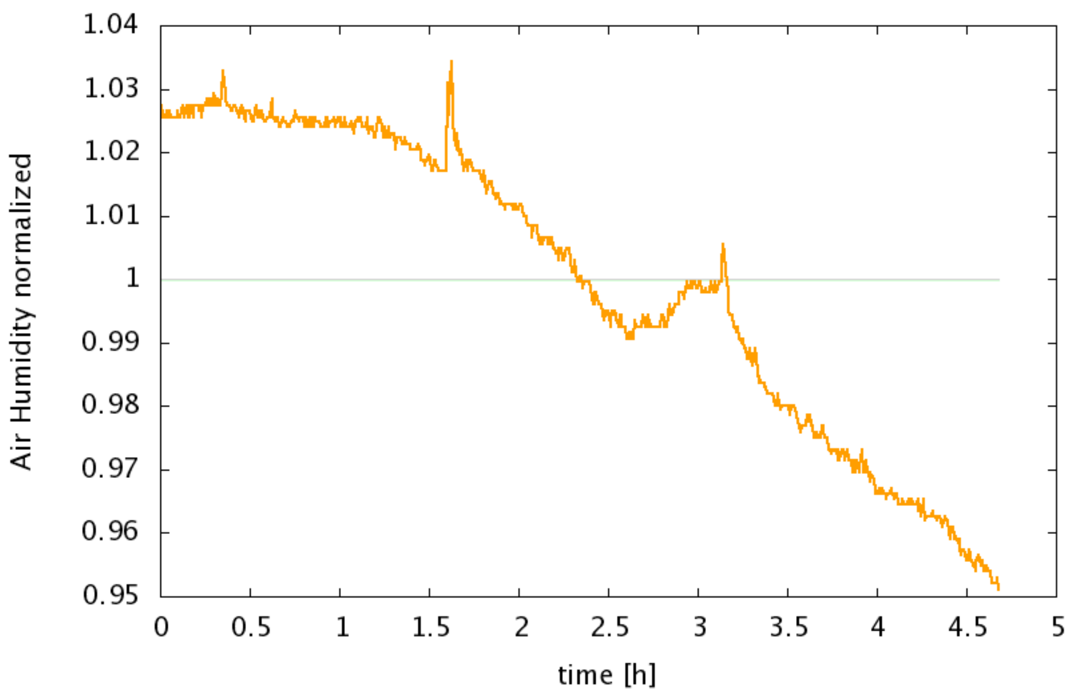
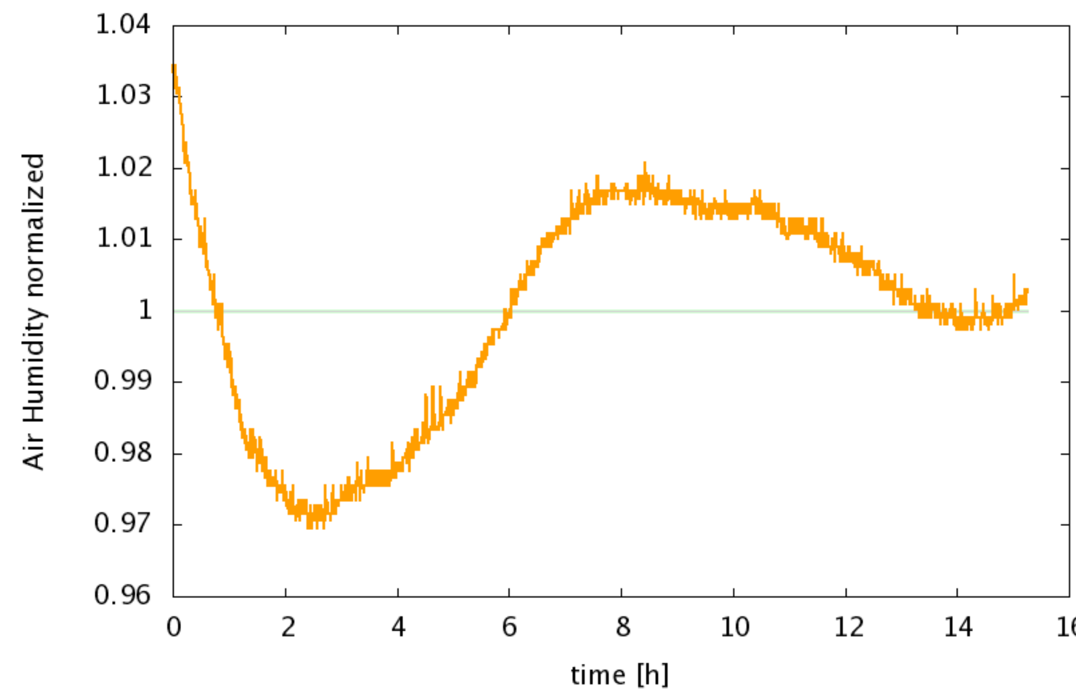
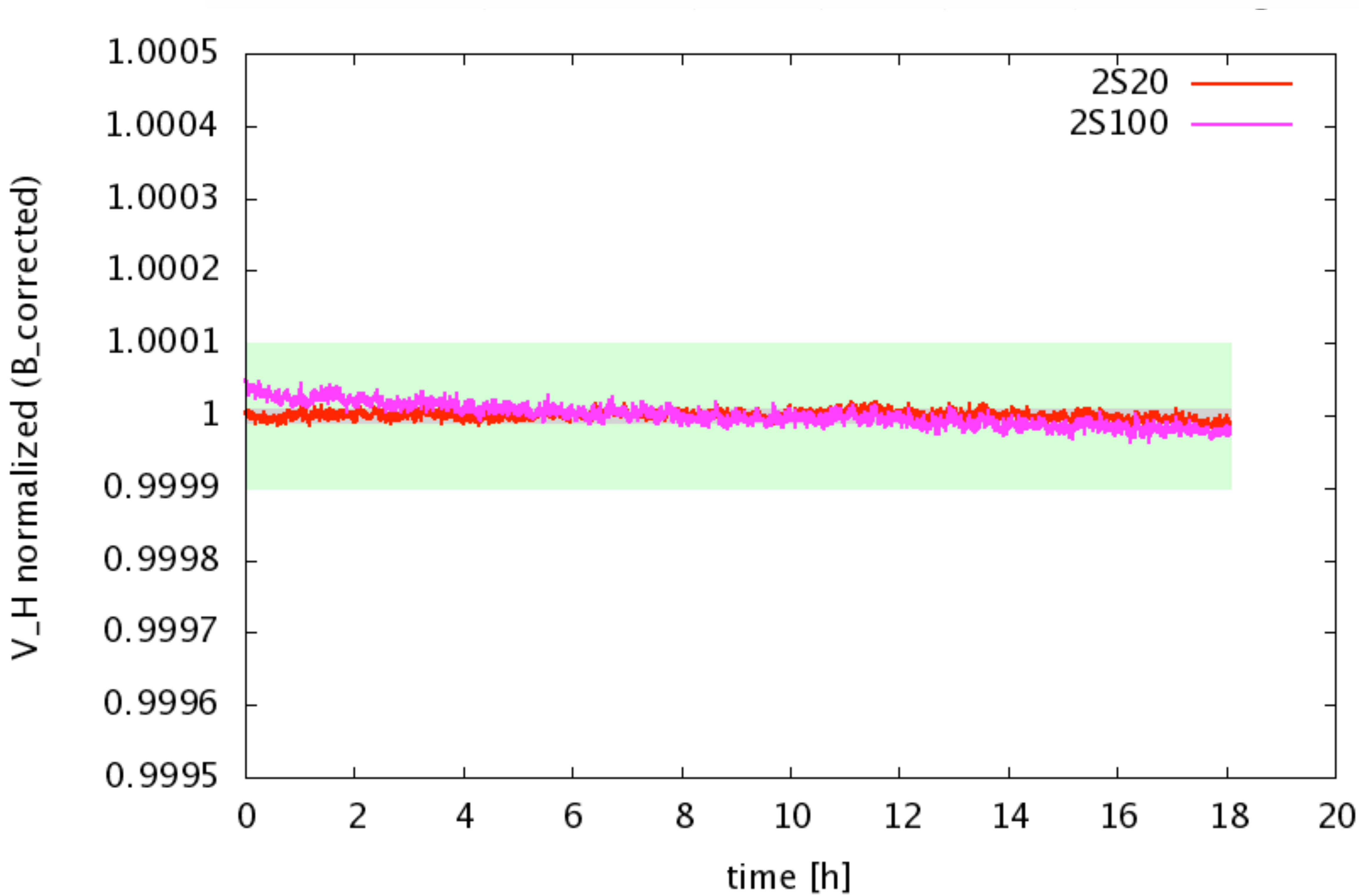








Thickness of SiN_x layer



Conclusions

- SiN_x (PECVD 300 °C) is crucial for long-term stability of the constituent GaAs Hall sensors in the Hallcube.
- Soldering at elevated temperature (in my case 400 °C) can severely degrade the of SiN_x layer and its passivation effect.
- (Insulated) Wire-bonding should be explored as an alternative to soldering.
- Removal of the GaAs cap layer seemingly has a further positive effect on sensor stability
- The SiN_x passivation layer should be <100 nm thick.
- No "ideal" thickness, if it exists, for SiN can be given yet from minimal testing.
- Sensor concept adaptable and also independent on semiconductor material, custom-made solutions possible.

- New, revised Hallcube version should be built now, parts have arrived (still confidential).

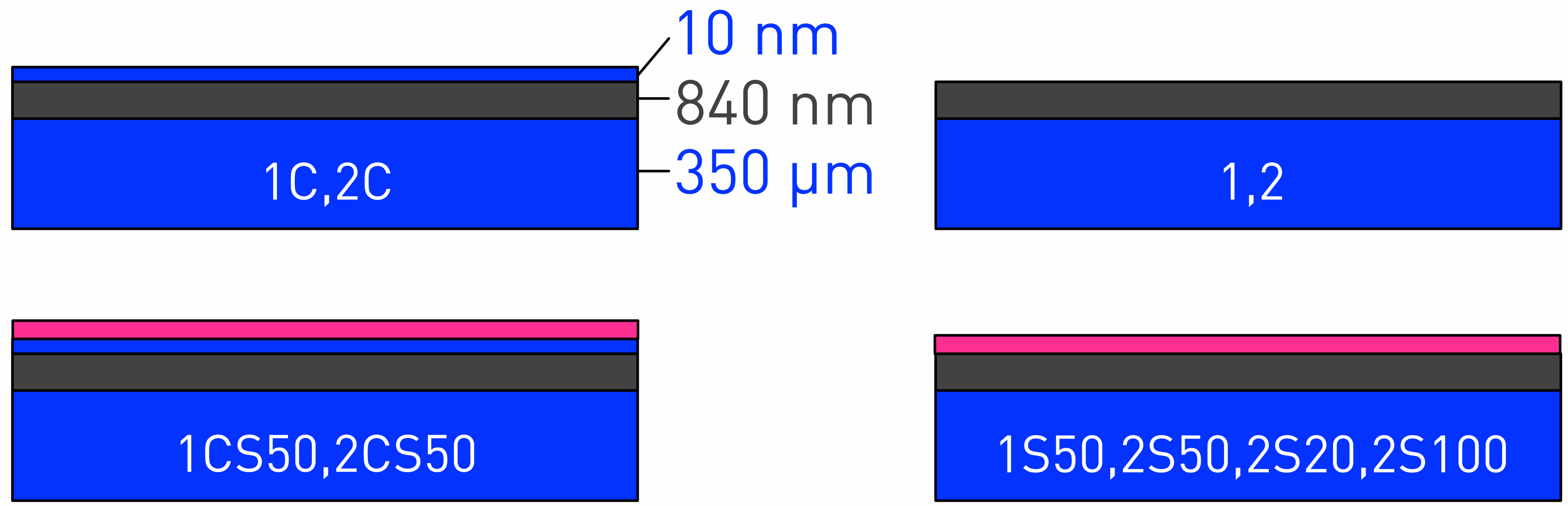
Approach

HPF6a wafer

Semi-insulating GaAs

n-type GaAs (Si: $n \approx 10^{17}$ cm^{-3})

SiN_x



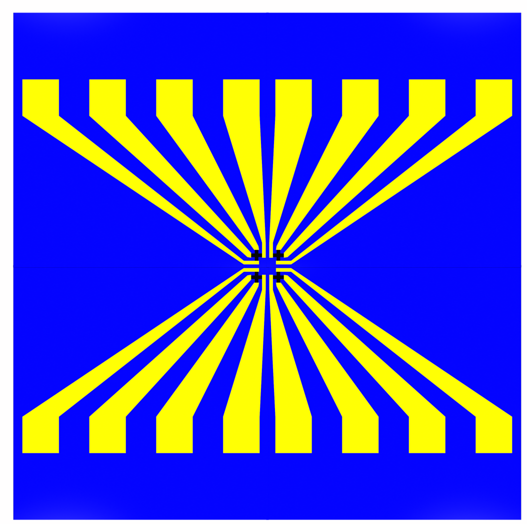
Repeatability on/among chip(s)

10 x 4 = 40 Hall crosses

- 1, 1S50, 1C, 1CS50
- 2, 2S50, 2C, 2CS50
- 2S20, 2S100

"C": Cap, "S": SiN_x, "50": 50 nm

Lost during processing: 2C, 3/4 of 2S50



Cap/mesa etch: piranha

SiN_x deposition: PECVD 300 °C

Ohmics: GeAuCrAu (e-beam evaporation)

"Packaging": epoxy, pcb, wire-bond

Considerations

Periodic field ⇨ high gradients, in this case up to 75 Tm^{-1}

$\boxed{\text{PHE compensation?}}$

200 µm spatial separation of Hall sensors

⇨ 150 Gauss difference in in-plane field component

Error < 0.3 Gauss and due to averaging < 0.15 Gauss

$\boxed{\text{Interpolation error?}}$

For *d* = 200 µm and for a tolerable error of 10^{-4}: fields up to 10.000 Tm^{-2}

getting close: 9475 Tm^{-2}

Measurement scheme U50

$$B_y = B_{\max} \sin\left(\frac{2\pi z}{\lambda}\right)$$

0.6 T   50 mm

at any position *s* along *z*:

$$B_{avg} = \frac{1}{\Delta} \int_{s-\frac{\Delta}{2}}^{s+\frac{\Delta}{2}} B_{\max} \sin\left(\frac{2\pi z}{\lambda}\right) \qquad B_{z=s} = B_{\max} \sin\left(\frac{2\pi s}{\lambda}\right)$$

B_{avg} - $B_{z=s}$ max at $s = \lambda/4$

B_{avg} - $B_{z=s}$ < 0.1 Gauss for Δ < 160 µm

for Hall voltage integration time 20 ms: v_{max} = 8 mm/s

Hall sensor data acquisition:
I_{Hall} = 0.1mA (Keithley 6221)
Hall voltages read by Agilent 3458A voltmeters
v_{scan} = 2.1 mm/s
External trigger every 112 µm (5000 points in 560 mm)

x = 0,+/- 0.5 mm
y = 0,+/- 0.125 mm
z = 0-560 mm